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**Cost-Benefit Analysis of Microgenerators;
An Integrated Appraisal Perspective**

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Cost-Benefit Analysis of Microgenerators; An Integrated Appraisal Perspective

Hassan Ali Harajli

A thesis submitted for the degree of Doctor of Philosophy
University of Bath
October 2009

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ABSTRACT

The UK domestic building sector accounts for a substantial amount of the final energy demand and greenhouse gas (GHG) emissions. To this extent, the sector can play an important role in GHG abatement and energy demand reduction, essential objectives of a more 'sustainable energy system'. Microgeneration, or production of electricity or heat from small-scale sources, have been advocated by some, including the Supergen 'Highly Distributed Power Systems Consortium' to which this thesis contributes, as important means towards achieving these objectives.

In this thesis, three assessed microgenerators; specifically a 600W microwind system, 2.1 kWp photovoltaic (PV) and building-integrated photovoltaic (BIPV) systems, and a 2.8m² solar hot water (SHW) system have been analysed through an 'integrated appraisal toolkit' in order to assess their respective economic and financial performance in current UK context. A cost-benefit analysis (CBA) is applied, based on outputs and results from energy analysis and life-cycle assessment (LCA), and other tools such as financial appraisal, cost-effective analysis (CEA), and simple multi-attribute ranking technique (SMART) are also performed in order to assess how these systems perform on an individual household level or when compared to other energy technologies.

The CBA, which included environmental impacts quantified through the LCA, obtained negative net present values (NPVs) for all the assessed microgenerators with the exception of microwind in a high-wind resourced 'open' area with lower end capital costs. The NPVs in the financial appraisal, which excluded environmental impacts, yielded relatively poorer results still. Only with the proposed feed-in tariffs would the systems all achieve positive NPVs.

Given that the CBA included a substantial qualitative part, alternative tools, such as CEA and multi-criteria evaluation were applied (in brief) in order to place the assessed systems in the context of other energy generating sources in the UK, and to enable a more confident decision with respect to whether these systems should be advocated or rejected.

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LIST OF ABBREVIATIONS

Abbreviation	Meaning
AC	Alternating current
AoP	Areas of Protection
BAU	Business as Usual
BAWT	Building augmented wind turbine
BC (ratio)	Benefit-cost (ratio)
BERR	Department for Business, Enterprise and Regulatory Reform
BWEA	British Wind Energy Association
BIPV	Building-integrated photovoltaic
BIS	Department for Business Innovation and Skills
BRE	Building Research Establishment
CASES	Cost assessment for sustainable energy systems
CBA	Cost-benefit analysis
CCGT	Combined cycle gas turbine
CCSA	Climate Change and Sustainability Act
CEA	Cost-effective analysis
CHP	Combined heat and power
CO ₂	Carbon dioxide
CS	Consumer surplus
CSERGE	Centre for Economic and Social Research on the Global Environment
DALY	Disability-adjusted life years
DC	Direct current
DECC	Department of Energy and Climate Change
DEFRA	Department of Environment, Food and Rural Affairs
DG	Distributed generation or deep green
DTI	Department of Trade and Industry
EC	European Commission
EE	Element Energy
EI-95	Eco-indicator 95
EI-99	Eco-indicator 99
ELU	Environmental load unit
EPA	Environment Protection Agency (US)
EPC	Energy Performance Certificates
EPS 2000	Environmental Priority Strategy 2000
ERA	Environmental risk assessment
EST	Energy Saving Trust
EU	European Union
FA	Financial appraisal
FITs	Feed-in tariffs
GDP	Gross domestic product
GHG	Green-house gases
HAWT	Horizontal-axis wind turbine
HiDEF	Highly Distributed Energy Future
HDPS	Highly distributed power systems
IEA	International Energy Agency
IPA	Impact pathway approach
IPCC	International Panel on Climate Change
ISO	International Organisation for Standardisation
IUCN	International Union for the Conservation of Nature
LC	Low carbon
LCA	Life-cycle assessment
LCBP	Low-Carbon Buildings Program

LCEGS	Low carbon and environmental goods and services
LCI	Life-cycle inventory
LCIA	Life-cycle impact assessment
MB	Marginal benefit
MC	Marginal cost
MCA	Multi-criteria analysis
MCE	Multi-criteria evaluation
MD	Marginal damage
MJ	Mega-joules
MOU	Memorandum of Understanding
MPC	Marginal private cost
MSC	Marginal social cost
NEA	Nuclear Energy Agency
NEEDS	New Energy Externalities Development for Sustainability
NMVOC	Non-methane volatile organic compounds
NPV	Net present value
NREL	National Renewable Energy Laboratory
OECD	Organisation for Economic Co-operation & Development
OFGEM	Office of the Gas and Electricity Markets
OPSI	Office of Public Sector Information
PAF	Potentially affected fraction
PCE	Parliamentary Commissioner for the Environment
PDF	Potentially disappeared fraction
PIU	Performance and Innovation Unit
PPM	Parts per million
PJ	Petajoule
PV	Photovoltaic or 'present value' (depending on context)
QL	Qualitative assessment
QN	Quantitative assessment
RAB	Renewables Advisory Board
REN21	Renewable Energy Policy Network for the 21 st Century
RHI	Renewable Heat Initiative
RHO	Renewable Heat Obligation
RO(C)	Renewables Obligation (certificate)
RPS	Renewable portfolio standard
SD	Sustainable Development
SEDBUK	Seasonal efficiency for domestic boilers in the UK
SERT	Sustainable Energy Research Team
SETAC	Society of Environmental Toxicology and Chemistry
SHW	Solar hot water
SCC	Social cost of carbon
SMART	Simple multi-attribute ranking technique
STC	Standard test condition
S-W index	Shannon-Weiner (S-W) index
UNEP	United Nations Environment Program
UK	United Kingdom
US	United States
WCED	World Commission on Environment and Development
WHO	World Health Organisation
WTA	Willingness to pay
WTP	Willingness to accept
VAWT	Vertical-axis wind turbine
YDL	Years of disability
YOLL	Years of life-lost

1 Introduction

1.1 Background

“Think global, act local” is a recognised catchphrase that attempts to capture a global problem and yet present the solutions as being determined at a local level. This phrase cannot be more applicable than in the matter of energy and climate change. The current concerns of climate change and its consequences on present and future human societies and natural ecosystems and species, coupled with concerns surfacing from energy security objectives, are bringing about a critical rethinking in the way society produces and delivers its energy. This re-evaluation of energy is part of the wider concept of ‘sustainable development’ which aims to balance economic, social and environmental considerations for both present and future generations.

Renewable and/or low-carbon energy systems, both large-scale and small-scale, are emerging to be one of the more promising solutions in our efforts to combat climate change while ensuring a continuous and secure supply of energy, and in specific for our case; heat and electricity to the domestic sector. Yet many of these systems, such as the ‘microgenerators’ (see Section 1.1.4) assessed in this thesis, are only just beginning to sufficiently improve on their technical potential. This improvement includes the ability of electricity (and heat) networks to actually accommodate many sources and many loads. However, most of these low-carbon energy systems, including the assessed microgenerators, have yet to compete, financially, against the more conventional sources of heat and electricity.

This study focuses on appraising selected microgenerators in the context of sustainable development, and in specific on the society-wide costs and benefits of installing the selected microgenerators in the UK domestic sector. The costs and benefits of microgenerators to a single householder are also considered through a financial appraisal, in order to have a clearer picture of the incentives (or lack of) of purchasing and installing these systems on an individual level.

Other tools, such as cost-effective assessment (CEA) and simple multi-attribute technique (SMART), are briefly discussed and applied in order to provide a clearer recommendation with respect to investing in the assessed microgenerators, and in order to enhance the ‘integrated appraisal’ decision-making capability.

1.1.1 Climate change

Climate change is defined by the Intergovernmental Panel on Climate Change (IPCC) as a ‘change in the estate of the climate that can be indentified (e.g. using statistical tests) by changes in the mean and /or the variability of its properties, and that persists for an extended period, typically decades or longer and could be brought about either naturally or as a result of human activity’ (IPCC Working Groups I-III, 2007). On a geological timescale, climate has always been in a state of ‘change’, and one of the factors promoting such change was and is the concentration of carbon dioxide (CO₂) in the atmosphere. The link between temperature and atmospheric CO₂ concentrations occurs due to the ability of CO₂ to absorb solar radiation through what is known as the ‘greenhouse’ effect. Carbon dioxide has always fluctuated on geological timescales in

the Earth's atmosphere, yet the current climatic concerns involve the significant and increasing CO₂ and other greenhouse gas (GHG) emissions from man-made sources, released in a short time (particularly since the industrial revolution) and in large amounts into the atmosphere. The atmospheric concentrations of carbon dioxide, methane, nitrous oxide and other GHGs have increased significantly due to human activity from a pre-industrial (1750s) level of 280 parts per million¹ (ppm) to a current level of 380 ppm (IPCC Working Group I, 2007). The average net effects of these emissions have led so far, with 'very high confidence', to global warming with a radiative forcing of between + 0.6 to about + 2.4 Watts/m² (IPCC Working Group I, 2007). The radiative forcing has translated into a total temperature increase of between 0.57 to 0.95°C from 1850-1899 to 2001-2005. This observed increase in global average temperature is very likely due to the increase in anthropogenic GHG concentrations (IPCC Working Group I, 2007). The IPCC presents several possible emission scenarios or models of temperature rise into the future as a function of perceived or projected global economic growth, population growth, environmental awareness and cooperation, natural assimilation assumptions (i.e., carbon sinks) and technological advancement and transfers among other parameters. The most optimistic (yet currently surpassed) scenario will bring about a further 0.6°C temperature increase by 2090-2099 compared with 1980-1999. Less optimistic scenarios will bring about 1.8°C to 2.8°C warming, while the more pessimistic scenarios forecast at least 3.4°C warming which could reach to 6.4°C warming within the same time period comparison (IPCC Working Group I, 2007).

Therefore, global warming is a current reality which is set to continue throughout this century. The severity of global warming will depend on both the actions or path that societies take in the near and medium term, coupled with the known (and unknown) natural responses such as carbon sink performances (e.g. the assimilative capacity of forests and oceans) and possible feed-back mechanisms in the form of lowered albedo and methane release due to the melting of snow and permafrost, respectively. Several estimates indicate that 'positive feedbacks' could lead to an additional rise in temperature of 1-2°C by 2100 (Stern, 2006).

Global warming can be thought of as an overarching environmental problem or crisis that impacts, or will impact, almost every single natural and socio-economic category from ecosystems and biodiversity to human health and well-being. These impacts are documented in the IPCC Working Group II report.

1.1.2 Sustainable development (SD) and SD objectives

'Sustainable development' (SD) is the currently stated intent of many modern economies, inherently implying that economic development can go hand in hand with the concept of 'sustainability' that is bought forth from ecological concerns about natural resources. Although SD has been defined in many ways, a commonly referred to definition is from the Brundtland² Report by the World Commission on Environment and Development (WCED);

¹ Parts per million (ppm) is the ratio of the number of GHG molecules to the total number of molecules of dry air.

² Gro Harlem Brundtland served as prime minister of Norway in the early 1980s and headed the World Commission on Environment and Development which was set up in 1983.

“Sustainable development is development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs” (WCED, 1987).

A brief history of sustainable development is presented in Appendix 1.

According to the Brundtland report, sustainable development is the new paradigm which can demonstrate that environmental protection and economic development are not mutually exclusive, yet are intrinsically linked, especially for the long term. In the UK, the government defined sustainable development as representing four simultaneous objectives being; (1) social progress including equality, (2) effective protection of the environment, (3) prudent use of natural resources, and (4) maintenance of high and stable levels of economic growth and employment (Parkin, 2000). These objectives lead to the most common way of depicting sustainable development through the three dimensions of a Venn diagram, as presented in Figure 1.1.

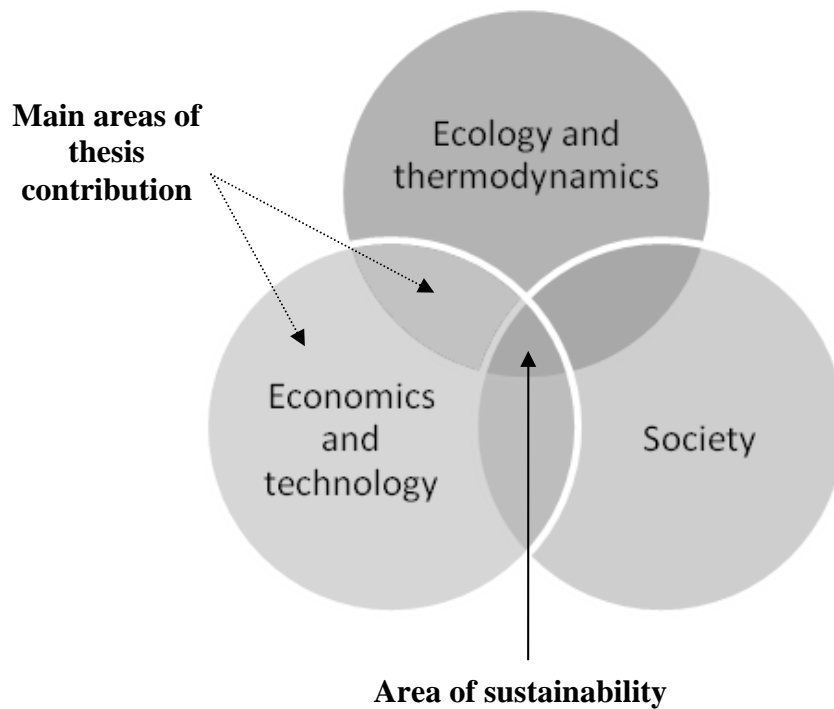


Figure 1-1 Sustainability Venn diagram for engineers
(Source: Parkin, 2000)

Figure 1.1 illustrates an engineering perspective to sustainability, where the economy and technology are assessed on par with ecological and social considerations. Overall, SD could be said to be a path unto which societies must strive to put themselves to reach the destination of sustainability. The only difference between the original Venn diagram for sustainable development (i.e., the simple environment-economy-society combination) and the illustrated engineering perspective in Figure 1.1 is that the latter is laying down the groundwork for sustainability assessment (Hammond & Winnett, 2006).

This sustainability framework is the overarching concept within which an ‘integrated appraisal’ of microgenerators is implemented in this thesis using energy analysis, life-cycle assessment (LCA), and cost-benefit analysis (CBA), in order to show the interconnections and constraints within the energy system (Allen *et al.*, 2008a, reproduced in Appendix 8). Social aspects of microgeneration are mostly beyond this study’s scope, however given their importance to the completeness of CBA, they are briefly addressed in Chapter 2.3 and Chapters 7 and 8.

1.1.3 Sustainable energy

From the most commonly used Brundtland report’s definition and concept of sustainable development, there is a need to interpret this definition or concept for energy and/or the energy system. There is more than one way of defining and characterising a ‘sustainable energy system’, and what constitutes this system is widely debated. In its most general terms, a sustainable energy system could be thought of in terms of its energy efficiency, its reliability, and its environmental impacts. The basic requirement of an energy system is to generate power for everyone at an affordable price while ensuring that that power is clean, safe and reliable (Alanne & Saari, 2006).

In a similar categorical manner, Acres (2007) applies a set of sustainable energy principles based on the energy hierarchy, providing a framework for practical decision-making in the energy sector (Acres, 2007). The energy hierarchy advocates the reduction in the use of energy first, to be followed by energy efficiency gains and measures second, to relying on renewable energy sources third and finally on non-renewable conventional energy sources under the best available ‘clean’ and ‘efficient’ technologies (Acres, 2007). Within this hierarchy, Acres (2007) proposes five principles, namely;

- *Zero net emissions of GHGs, i.e., no contribution to climate change;*
- *No significant environmental impacts, meaning that all emissions within carrying capacity of surroundings;*
- *Enhances security of supply due to the fact that ‘this is key to everyday life and wellbeing... as supply interruptions are a major problem for society (i.e., a social perspective);*
- *Reduces costs of energy supply and improves access to energy supply, which from an economic perspective, focuses on the affordability of energy supply in the context of industrial competitiveness, and attention to the more vulnerable in society who spend near or more than 10% of their income on energy;*
- *Harnesses renewable energy as much as possible.*

Acres (2007) concludes that there is ‘no magic bullet’ for energy, but that the energy hierarchy and the outlined five principles above enable us to distinguish technologies between (1) indefinitely sustainable, (2) ultimately unsustainable but tolerable for a significant period, and (3) highly unsustainable and a priority for early phase out (Acres, 2007).

Mitchell (2008) on the other hand indicates some important differences between ‘conventional’ and ‘sustainable’ electricity systems which could clarify and differentiate the characteristics of each. A conventional system is characterised by a

top-down system which focuses on supply-side solutions and delivery, with large conventional plants (most of which need time to ramp up) connected to the ‘passive’ transmission (and distribution) network to customers who see energy simply as being present at a touch of a switch. Concerns about energy security are met by additional conventional generation and environmental externality concerns are regarded minimally. The over-all market under a conventional system is likely to be a government-owned monopoly offering little consumer choice and unworried about risks or losses due to continuous government support (Mitchell, 2008). On the other hand, a sustainable energy system is characterised by publicly aware citizens that see the connections between energy and the environment and who use energy efficiently. Within this system, the environment plays a greater role and is an important driver of policy, while energy security concerns are answered through the diversification of generation technologies, including large-scale and distributed renewables sources, the reduction in dependence on imported oil, and targeting demand reductions through behaviour change or energy efficiency measures. The sustainable energy system will contain different technologies and sizes, connected to both the transmission and the distribution networks which become in themselves ‘active’. The market structure for the sustainable system is liberalised and privatized, where choice is given to customers (competition) and risks are faced by the private companies themselves (Mitchell, 2008).

A sustainable energy system therefore would have to balance several parameters, most notably the consideration or the factoring in of future generations, environmental impacts including greenhouse gas emissions, social implications, economic costs, and energy security.

1.1.4 Microgeneration

The UK domestic building sector accounts for approximately 30% of the UK’s final energy demand and 23% of UK GHG emissions (Allen *et al.*, 2008a). To this extent, the sector can play an important role in carbon dioxide abatement and demand reduction in the UK, essential goals for a sustainable energy system.

Decentralised or distributed energy supply refers to the generation of energy close to the point of use through generators as large as community sized or district-level systems down to the individual household generator. Microgeneration on the other hand is defined in Section 82 of the UK’s Energy Act (2004) as the production of electricity or heat from a low-carbon source, at capacities no more than 50kW_e or 45kW_{th} (Allen *et al.*, 2008a). The term embraces a variety of technology options, including micro-wind turbines, solar photovoltaic (PV) arrays, solar hot water (SHW) systems, micro-combined heat and power (CHP) units, and heat pumps. Some of these technologies are based on renewable resources (which are essentially ‘zero carbon’), while some increase the energy efficiency of fossil fuel use and are thus considered ‘low carbon’ options (Allen *et al.*, 2008b). The Energy Saving Trust (EST) suggested that micro-generators could meet 30 – 40% of the UK’s electricity requirements by 2050 (EST *et al.*, 2005).

The Supergen Highly Distributed Power System (HDPS) Consortium envisions a supply contribution of ‘distributed sources’, specifically district heating schemes and microgeneration, to the residential sector demand between 29% - 79% for heat and

23% - 44% for electricity by 2050 depending on which scenario (Business as Usual, Low Carbon, or Deep Green) actualises (Jardine, 2006). This study is part of the wider Supergen HDPS consortium, which includes power-flow analysis and multicriteria analysis (MCA), as shown in Figure 1.2.

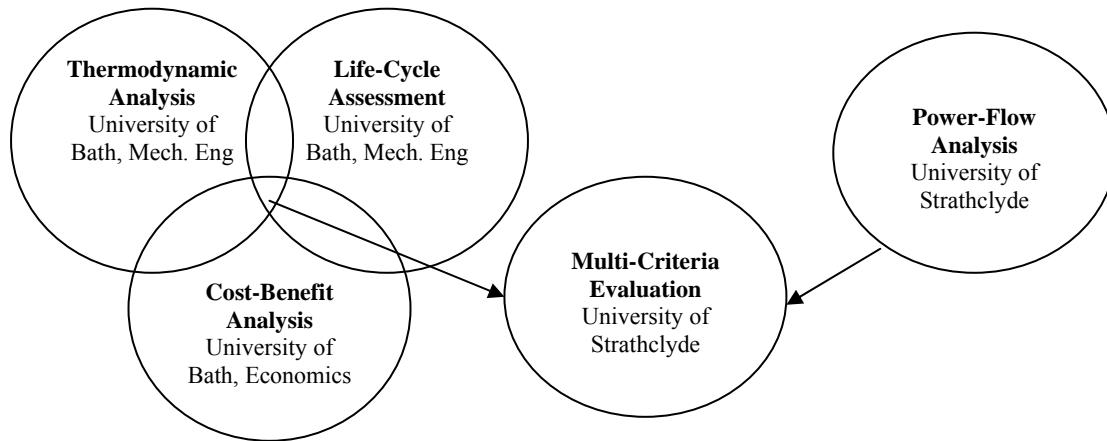


Figure 1-2 Supergen HDPS: Integrated appraisal methodology and responsible institution
(Source: Allen *et al.* 2008a)

Figure 1.2 shows the Supergen HDPS project, and the institutions responsible for implementation. The project envisions large numbers of independently owned and operated generators connected across all voltage levels within the distribution network. Some recent publications of this consortium can be found in a special issue of proceedings of the UK's Institution of Mechanical Engineers (Burt *et al.*, 2008). The focus of this thesis is on cost-benefit analysis (CBA), however linkages to thermodynamic analysis and life-cycle assessment would be necessary to perform this task. Furthermore, a simple multi-criteria evaluation (MCE) would be implemented in Chapter 8 to provide for better decision-making with respect to the assessed microgenerators.

1.2 Aims, Objectives, and Structure

The primary aims of this thesis are to (1) perform an economic assessment and financial appraisal of several microgenerators in the UK residential sector, and (2) to contribute to the 'integrated appraisal' framework for microgenerators by linking two of the three dimensions of sustainable development, specifically the 'ecological and thermodynamic' dimension, i.e., energy analysis and life-cycle assessment, with the 'economic and technology' dimension, i.e., the economic cost-benefit analysis and financial appraisal. This was indicated diagrammatically in Figure 1.1.

The objective of the thesis is to show how the selected microgenerators, specifically the 600W microwind system, 2.1 kWp PV and BIPV systems, and the 2.8m² SHW system perform in the current UK economic and financial context. These systems can be installed on old or new build in the UK domestic sector with the exception of BIPV, which can only be installed on new build.

The three micro-generator types were selected by Bath's Sustainable Energy Research Team (SERT), including the author, for their potential vital role in delivering low-carbon electricity and heat to the UK domestic sector. The more recent Supergen Highly Distributed Energy Future (Hi-DEF)³ project will look at alternative microgenerators through a similar integrated toolkit as that used in this thesis. The technologies were selected through a Memorandum of Understanding (MoU) between SERT and the respective manufacturers' of these microgenerators. The PV, BIPV, and SHW systems could be considered representative of the technologies' types, given their size and ability to generate significant electricity to the UK householder. On the other hand, the 600W microwind system could not be considered representative of the UK domestic market for microwind given its smaller size and higher capital costs. The 600W microwind system assessed in this thesis was selected by SERT given the high-level of cooperation achieved with its' manufacturer that could not be obtained from other manufacturers of microwind systems of larger sizes. To compensate for this shortcoming, a brief overview of more representative microwind systems is presented in this thesis as well.

With respect to the economic context, the objective of this thesis is to fully implement a cost-benefit analysis (CBA) on the three above systems (assuming PV and BIPV are in the same system category, although differentiated in this study). In order to complete a CBA, direct and indirect costs and benefits that will accrue to society at large from these systems are addressed, quantitatively and qualitatively. In specific, the CBA involved the following;

- The linking of LCA inventory data and life-cycle impact assessment (LCIA) results to CBA through four author-selected and alternative approaches of environmental quantification and monetization, each approach with its own advantages and disadvantages. This involved in-depth research as to the compatibility of LCA output into CBA, a requirement for the enhancement of the 'integrated appraisal' methodology;
- The estimation of the 'value' for electricity and hot water, as opposed to the displaced (or financial) benefits that are always used, as a conservative estimate, in CBA of energy-related sources in the literature, including Allen *et al.* (2008a). Eliciting the 'value' of electricity and hot water, although contentious given the need to theoretically construct a demand curve, is thought to better represent the benefits of the microgenerators to individuals in society, as opposed to the use of displaced energy;
- A qualitative assessment of other important attributes that could not be monetized, such as psychological implications and employment generation, or attributes that are monetized, yet not with enough confidence to have been included in the quantitative part of the CBA;
- An innovative author-established method for accounting for positive *learning externalities* from installing these systems;
- A recommendation based on the CBA results

A parallel objective of this study is to show how these microgenerators perform relative to other energy generating sources through cost-effective analysis (CEA), and how they perform on an individual private level through a simple financial appraisal,

³ Please see; <http://www.supergen-hidef.org>.

which includes the additional influences of current and proposed UK government-led financial support mechanisms and levels. The amount of government-led financial support provided to the microgenerators is compared with the environmental damage costs estimated in the CBA, to assess whether marginal costs are at least equal to the expected marginal benefits.

Last, the study presents a simple multi-attribute rating technique (SMART) to present an alternative decision-aiding tool, given that the CBA involved a qualitative part which could be argued to undermine the thoroughness of using the *net present value* (NPV) as an indicator of whether or not the assessed microgenerators should be given the ‘*go-ahead*’ decision.

Much of the work in this thesis has been published in journal papers and conference proceedings, specifically Allen *et al.* (2008a), Hammond *et al.* (2009a), and El-Fadel *et al.* (2009) or are awaiting publication, specifically Allen *et al.* (2009) and Hammond *et al.* (2009b)⁴, all reproduced in Appendix 8. Much of the work presented here is based on these papers and would regularly refer to them.

The thesis structure follows the below chapters;

- Chapter 2. Integrated Appraisal of Microgenerators; Methods; outlines the theoretical underpinnings of the appraisal techniques used, mainly (1) energy analysis, (2) LCA, and (3) CBA (the main focus of this thesis);
- Chapter 3. Discusses and selects four approaches for linking LCA inventory data and/or impact results into CBA, with an assessment of the strengths and weaknesses of the approaches;
- Chapter 4. Outlines and describes the assessed microgenerators, their expected energy outputs and the LCA outputs under the four selected approaches;
- Chapter 5. A CBA is performed on the microgenerators, involving the elicitation of the ‘value’ of electricity and hot water, and the separation of the analysis through the four selected approaches. A sensitivity analysis is also performed on identified parameters;
- Chapter 6. A financial appraisal of the microgenerators is performed, assessing the systems without government support, with current financial support mechanisms, and with future proposed support. A comparison between the amount of support given and the expected environmental benefits of the microgenerators is also presented;
- Chapter 7. A qualitative analysis is performed as part of the CBA. Many attributes that could not be quantified in the CBA are either discussed qualitative in this chapter, such as employment benefits, or monetized either through innovative means (e.g. positive learning externalities) or monetized yet with insufficient confidence in the results to be included in the original CBA;
- Chapter 8. A cost-effective analysis (CEA) and a simple multi-attribute technique (SMART) are performed to enable better decision-making concerning the overall performance of the assessed systems in context with other energy generating sources;
- Chapter 9. Conclusions and future recommendations are presented, including a general discussion on the findings of the ‘integrated appraisal’.

⁴ Author order in published (or to be published) work is alphabetical.

2 Integrated Appraisal of Microgenerators; Methods

This chapter provides the theoretical foundations behind the methods applied here through the ‘integrated appraisal’ of the assessed microgenerators. Energy analysis and life-cycle assessment, which belong to the thermodynamics and ecology dimension of sustainable development as shown in Figure 1.1, will be addressed first in Sections 2.1 and 2.2. These are followed by a concise description of social appraisal techniques, which will not be addressed in this thesis. Cost-benefit Analysis (CBA), the main focus of this thesis, and other economic appraisal tools are discussed in more detail in Section 2.4. A brief reference to multicriteria evaluation (MCE) is addressed in Section 2.5.

2.1 Energy Analysis

The assessed microgenerators’ primary objective is to deliver energy to society. An important criterion to assess how effectively these microgenerators provide this energy is to compare their respective energy output(s) with the amount of energy it took in producing them in the first place. This comparison is part of what is known as energy analysis or energy accounting. More formally, energy analysis is a “systematic way of tracing the flows of energy through an industrial system, resulting in the apportioning of a fraction of the primary energy inputs into the system to each of the outputs of that system” (Roberts, 1978). In other words, the aim of energy analysis is to “evaluate the total amount of primary energy that is required to provide a given product or service” (Mortimer, 1991).

A simplified example of energy flows in the UK is illustrated in Figure 2.1 (Hammond, 2000a). Non-renewable natural resources are used to generate either heat (e.g. natural gas or oil providing fuel for domestic sector boilers) or electricity for all the sectors in an economy; transport, domestic, service, and industrial. Renewable energy sources (i.e., direct solar energy, wind and biomass) also add to electricity generation in the transformation system.

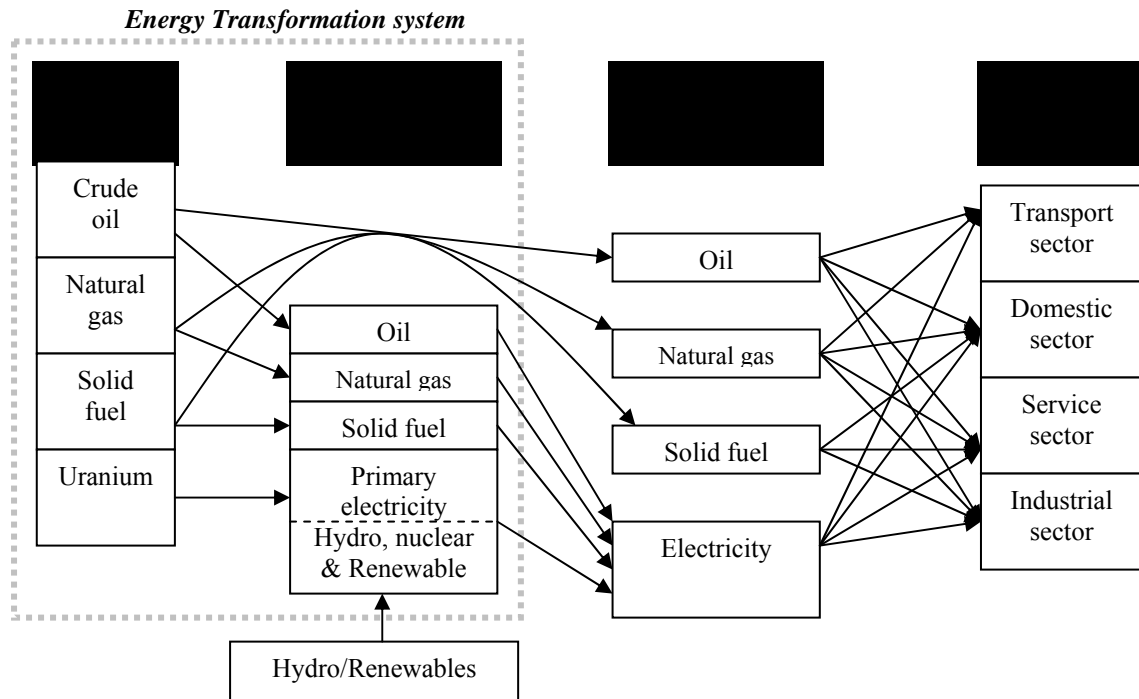


Figure 2-1 Simplified representation of the UK energy system
(Source: Hammond, 2000a)

A boundary is drawn around the process under consideration in Figure 2.1 and energy inputs are measured as they cross over this boundary (Mortimer, 1991). Primary energy inputs can be defined as downstream end-use or delivered energy plus upstream waste heat. Waste heat or energy loss occurs “at each stage of energy conversion and distribution, particularly in the process of electricity generation” (Hammond, 2000a). This is based on the First Law of Thermodynamics (or the Law of Conservation of Energy) where the total quantity of energy remains unchanged when being transformed from one form to another and therefore enables energy or heat losses to be estimated. It follows that the “overall performance of an energy system can be represented in terms of efficiency”, as presented in Equation 2-1.

$$\text{Overall energy system efficiency} = \frac{\text{Energy supplied to final consumers}}{\text{Primary energy consumed}} \times 100\% \quad \mathbf{2-1}$$

Table 2.1 indicates the primary energy consumed in the UK, the energy overhead (i.e., the losses due to conversion inefficiencies and transmission losses) and the subsequent overall efficiency of the system. The energy system’s efficiency has been more or less constant since the 1960’s, falling about 2% from the 1960 level in the 1970s and 80s, yet gaining this lost ground again by 2007 as shown additionally in Table 2.1 (Hammond, 2000a). The fall in the 1970s and 80s is attributed to “the greater use of electricity in the industrial sector albeit generated by newer power plants with higher efficiency” (Hammond, 1998).

	Year				
	1965	1975	1985	1995	2007*
Primary energy consumed (PJ) ⁵	8046	8521	8665	9183	9870
Energy supplied to final consumers (PJ)	5662	5893	5940	6318	6891
Energy overhead (PJ)	2384	2628	2725	2865	2979
Overall energy system efficiency (%)	70.4	69.2	68.6	68.8	69.8

Table 2.1 Overall performance of the UK energy system
(Source: Hammond, 1998, except*: BERR, 2008a)

Energy analysis ultimately will lead to the assessment of the entire life-cycle of the product or activity, from ‘cradle to grave’ (Allen *et al.*, 2008a), and will enable the identification of feedback loops such as the indirect (embedded) energy requirements for materials and capital outputs (Hammond, 2000a). This procedure will lead in the end to the estimation of the product or activity’s ‘gross energy requirement’ (GER). The GER can be defined as “the life-cycle primary energy inputs required to deliver a good or service to the point of interest”, defined by Equation 2-2 (Allen *et al.*, 2008c).

$$\text{GER} = \frac{\text{Life - cycle primary energy input (MJ)}}{\text{Delivered energy (MJ)}} \quad 2-2$$

The GER contains the embodied energy of the original source of energy as opposed to the Net Energy Requirement (NER) which excludes this energy content (i.e., NER is equal to GER minus the energy content of the assessed product). Two further metrics that are beneficial in energy analysis are the ‘energy gain ratio’ (EGR), and the ‘energy payback period’ (EPP). The EGR is defined “as the energy output from a generator over its lifetime divided by the total primary energy input (inverse of GER)” while the EPP is “analogous to a financial payback period representing thus the number of years that a system must operate until its energy output equals the GER” (Allen *et al.*, 2008c). The ‘energy gain ratios’ for the microgenerators are discussed in Chapter 8 through the SMART.

2.2 Life-Cycle Assessment (LCA)

Life-cycle assessment (LCA) was codified under the auspices of the ‘Society of Environmental Toxicology and Chemistry’ (SETAC) at a series of workshops in the early 1990s and is defined as follows;

“LCA is a process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and materials used and wastes released to the environment; to assess the impact of those energy and material uses and releases to the environment; and to identify and evaluate opportunities to affect environmental improvements. The assessment includes the entire life cycle of the product, process, or activity, encompassing extracting and processing raw materials, manufacturing, transportation and distribution, use, re-use, maintenance, recycling and final disposal” (SETAC, 1993).

⁵ Abbreviations: PJ = petajoule (10¹⁵J)

LCA had its origins in the 1960s and 1970s through studies that aimed to quantify industrial use of raw materials and energy, particularly after environmental and natural resource concerns addressed in publications such as ‘Resources and Man’ (Freeman, 1969), the ‘Limits to Growth’ (Meadows *et al.*, 1972), and the ‘Blueprint for Survival’ (Goldsmith & Allen, 1972) (SETAC, 1993). The most prominent studies (or projects) at that time which set the ground-works for LCA were implemented by Coca-cola in 1969, Boustead and Hancock (milk) in the UK in the 1970s, and Sundstrom (beer) in Sweden in 1973 (SETAC, 1993). All studies assessed alternative container systems via a ‘cradle to grave’ methodology that was referred to then as ‘Resource and Environmental Profile Analysis’ in the US or ‘Ecobalance’ in Europe and which is referred to today as life-cycle inventory, a part of LCA (EPA, 2006; SETAC, 1993). However it wasn’t until the early 1990s that a standard technical framework for conducting LCAs was developed through SETAC, as was the term ‘life cycle assessment’ coined. The demand for the standardization of this technical framework (i.e., the LCA methodology) was thereafter implemented by the International Organization for Standardization (ISO) through its 14000 series (EPA, 2006).

LCA is used to quantify the amount of energy and materials used, and pollutants or wastes released into the environment as a consequence of a certain product or service over the whole life cycle, i.e., ‘from cradle to grave’ (Allen *et al.*, 2008a). Figure 2.2 illustrates the life-cycle stages of a product or process, beginning with the required inputs of raw materials and energy through the processes and consequences of manufacturing, use, reuse, maintenance, recycling, and disposal (including the transportation requirements in-between) to the final outputs in the form of air, water or solid pollutants (EPA, 2006).

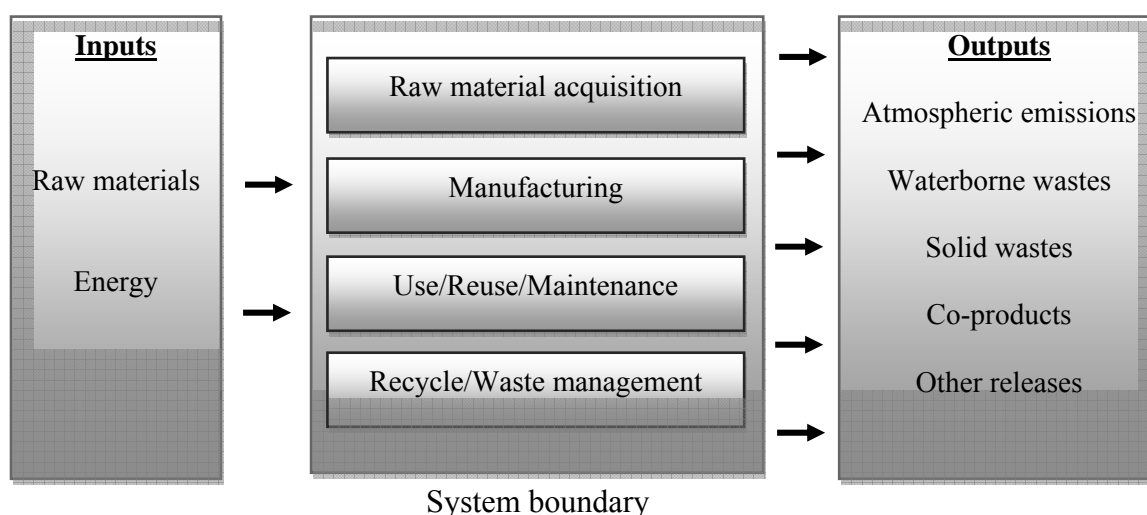


Figure 2-2 Life-cycle stages of products or services
(Source: EPA, 2006)

The LCA process is a systematic and phased approach which consists of four main components; goal definition and scoping, inventory analysis, impact assessment, and interpretation as illustrated in Figure 2.3 (ISO 14040, 2006) and described in the proceeding text.

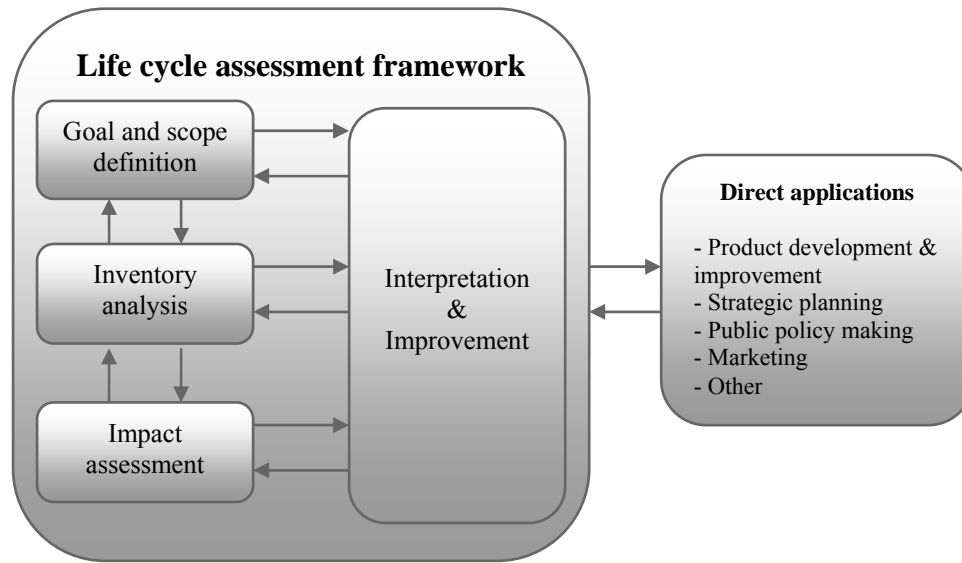


Figure 2-3 Phases of an LCA
(Source: ISO 14040, 2006)

2.2.1 Goal definition and scoping

The goal and scope of the LCA is defined early in the assessment by the LCA practitioner, indicating the intended application, the reason for undergoing the LCA, and the audience to whom the results would be targeted or communicated to (ISO 14040, 2006). This in turn will guide the entire process and determine the amount of time and money required for the assessment.

There are several main decisions to be made in the ‘goal and scope stage’ of a LCA. The first such decision is ‘defining the goal of the project’, which is usually either to ‘choose the best product, process, or service with the least effect on human health and the environment’ or ‘to assist in the development of new products, processes, or activities with reduced resource requirements and emissions’ (EPA, 2006). Other secondary goals for implementing an LCA are to (1) support broad environmental assessments, (2) establish baseline information for a process, (3) support public policy, (4) support product certification, and/or (5) to guide product and process development among others (EPA, 2006).

Second and thirdly, the ‘goal and scope’ stage of the LCA will need to ‘determine what type of information is needed’ for the particular indicated set goal and ‘determine the level of specificity’, for example, will the study be completely generic or product-specific? (EPA, 2006) Information and specificity issues are usually guided by the intended audience, whether for internal organisational use only or for public purposes (or both), the latter requiring more accuracy in the results.

Fourthly, the ‘functional unit’ is needed and is defined in such a way that appropriately describes the function of the product or process and allows for comparability between products or processes (EPA, 2006). The primary purpose of a functional unit “is to provide a reference to which the inputs and outputs could be related and normalized” (ISO 14044, 2006). With respect to comparing the pros and

cons of various energy sources, the functional unit could be mega-joules (MJ) of energy for example.

The 'scope of the LCA study' includes assessing the system boundaries which is usually dependent on the goal of the study, the required accuracy of the results, and the availability of time and resources (EPA, 2006). Figure 2.2 above illustrates a common system boundary that could be included in a project that includes raw material acquisition, manufacturing (materials manufacture, product fabrication, and filling, packaging and distribution), use and reuse, maintenance, and recycling or waste management (EPA, 2006). A process flow diagram that shows the unit processes and their inter-relationships is often used in LCA to assist in setting the system boundary (ISO 14044, 2006).

2.2.2 Life-cycle inventory

The second phase of the LCA as shown in Figure 2.3 is the 'life-cycle inventory analysis' (LCI) where the bulk of the data collection and analysis is performed. LCI is a "process of quantifying energy and raw material requirements, atmospheric emissions, solid wastes, and other releases for the entire life cycle of a product, process or activity" (EPA, 2006). LCI commences by collecting data for each unit process that is included within the system boundary – ideally as outlined through a flow diagram - to quantify the inputs and outputs of that unit process (ISO 14044, 2006). A data collection plan for each unit process is needed thereafter, where data quality goals are defined against the overall available time, resources and set objective and audience of the study (e.g. internal use versus public use). Data types include, yet are not limited to, measured data, modelled data, and sampled data or surrogate data. Data sources may include government documents, reports, databases, journals, books, laboratory test results, trade associations, industry reports or data, equipment and process specifications and operating logs or journals, meter readings, and LCA databases (software) among others (EPA, 2006). The data will need to be checked for validity to 'confirm and provide evidence that the data quality requirements for the intended application have been fulfilled' (ISO 14044, 2006).

2.2.3 Life cycle impact assessment

The third phase of LCA is the life cycle impact assessment (LCIA) phase. LCIA is the 'evaluation of potential human health and environmental impacts – including resource depletion – of the environmental resources and releases identified in the LCI through the concept of a stressor that is defined as a set of conditions that may lead to an impact' (EPA, 2006). Figure 2.4 illustrates the key and optional elements in a LCIA; selection and definition of impact categories, classification, characterisation, normalisation, grouping and weighting (ISO 14040, 2006).

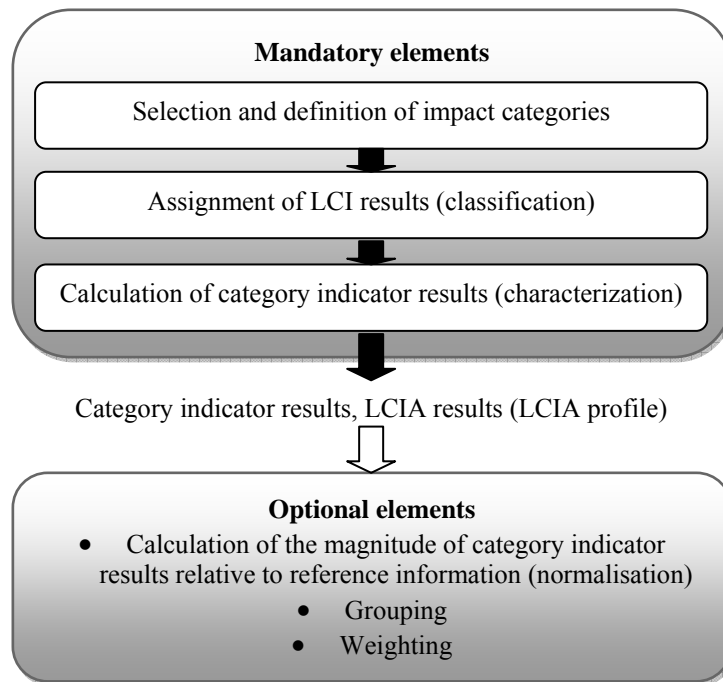


Figure 2-4 Elements of the LCIA phase
(Source: ISO 14040, 1997)

The selection of impact categories are ‘defined as the consequences that could be caused by the input and output streams of a system on human health, plants, and animals, or the future availability of natural resources’ (EPA, 2006). Classification, or the second step of LCIA as identified in Figure 2.4 aims to organise and combine the LCI results into impact categories (EPA, 2006). On the other hand, characterization uses conversion factors (or equivalency factors) to convert and combine the LCI results into pre-defined categories (EPA, 2006).

The first three steps of the LCIA are mandatory while the remaining three steps are optional according to the EPA (2006), yet not recommended by ISO 14040 (2006). Of the latter, normalisation is used to ‘express impact indicator data in a way that can be compared among impact categories’ (EPA, 2006). In other words, normalisation calculates the magnitude of the category indicator results relative to some reference information (ISO 14044, 2006). The reference values could be (1) “the total inputs and outputs for a given area that may be global, regional, national or local, or (2) the total inputs and outputs for a given area on a per capita basis, or (3) inputs and outputs in a baseline scenario such as a given alternative production system” (ISO 14044, 2006).

‘Grouping’ thereafter ‘assigns impact categories into one or more sets as predefined in the goal and scope phase, possibility involving sorting and/or ranking’ (ISO 14044, 2006). Specifically, ‘grouping’ sorts the impact categories either on a nominal basis (by characteristics such as inputs and outputs or spatial scales) or through the ranking of impact categories in a given hierarchy (e.g. high, medium, and low priority) (ISO 14044, 2006).

Finally, ‘weighting’ could conclude the LCIA by converting indicator results of different impact categories by using numerical factors based on value-choices (ISO 14044, 2006). This is done either by converting the indicator results or normalised results with selected weighting factors, or through aggregating converted indicator results or normalised results across impact categories (ISO 14044, 2006).

The LCIA phase is revisited in detail in Chapter 3, specifically as two LCIA methods are selected and inputted into the CBA.

2.2.4 Life cycle interpretation

Life cycle interpretation is a “systematic technique to identify, quantify, check, and evaluate information from the results of the LCI and the LCIA, and communicate them effectively” (EPA, 2006). The interpretation phase consists first of identifying the significant issues (i.e., the elements that contribute most to the impact results) such as energy usage, emissions, and resource use based on the LCI and LCIA results and in line with the defined goal and scope of the study (ISO 14044, 2006). Secondly, an evaluation step in the interpretation phase aims to establish confidence in and reliability of the results of the LCA or the LCI study through completeness, sensitivity and consistency checks. The completeness check ensures that all relevant information and data needed for interpretation are available and complete. If important information is missing, either a revisiting of the LCI and LCIA phase is recommended or an adjustment in the defined goal and scope (ISO 14044, 2006). Sensitivity check on the other hand ‘assesses the reliability of the final results and conclusions by determining how they are affected by uncertainties in the data, collection, allocation method or calculation of category indicators results among others’ (ISO 14044, 2006). A consistency check is required thereafter to determine whether the assumptions, methods and data are consistent with the goal and scope. Finally in the interpretation stage, the ‘conclusions, encountered limitations and recommendations’ are put forth which ultimately identify the significant issues of the study, evaluate the methodology used, and indicate the completeness, sensitivity and consistency of the results. Preliminary conclusions are first arrived at which, if in line with the goal and scope of the study, would be considered the final conclusions of the study (ISO 14044, 2006).

2.2.5 SimaPro software and Ecoinvent database

The software SimaPro 7.1 was employed by the Sustainable Energy Research Team (SERT) at the University of Bath for the LCA of the microgeneration systems covered in this thesis. SimaPro is a commercially available package which “enables the manipulation and examination of inventory data in accordance with the ISO LCA Standards” (Allen *et al.*, 2008a). The database for the assessment relied on the ecoinvent 2.0 database (as well as information from the manufacturers of the assessed microgenerators) which contains inventory data on energy supply, resource extraction, building materials and other material supplies, chemicals, waste management services and transport services among others entities (Althaus *et al.*, 2007).

The Eco-Indicator 95 was the main method used in Allen *et al.* (2008a and 2009), and Hammond *et al.* (2009a), all reproduced in Appendix 8. However, this thesis has

recommended alternative and arguably more appropriate LCIA methods for the CBA in order to better combine the methods within the 'integrated framework', particularly pushing for the use of the Eco-Indicator 99 LCIA method (see Hammond *et al.*, 2009b) and the EPS 2000, as discussed in Chapter 3. Furthermore and at the time of writing, the Eco-Indicator 95 LCIA method could be considered a superseded method, requiring therefore the use of newer LCIA methods, such as the Eco-Indicator 99.

2.3 Social appraisal

Within the context of sustainability, in which the integrated appraisal of microgenerators is placed, social considerations should be given equal footing as do economic and ecological concerns (see Figure 1.1). Energy and access to energy have very important implications, both positive and negative, for people and societies. On the one hand, energy and the access to affordable energy is 'arguably' considered a basic human right (Acres, 2007) which is inherently linked to general well-being, economic development, and social progress. Yet on the other, energy and power generation can have significant impacts (depending on generation type, location and so forth) on human health, demographics, safety, and general well-being through either local pollution (including noise) or the continuous release of greenhouse gases (GHG).

Assessing, quantifying and even monetising the potential social implications of microgenerators are not only necessary for the integrated appraisal yet are also necessary for cost-benefit analysis. Some negative social impacts from identified emissions of power sources have been internalised and monetised to a certain extent through the ExternE and NEEDS projects (see Chapter 3) and are included also within the 'social cost of carbon' concept visited in Chapter 3. However, a systematic and methodological approach, such as social impact assessment (SIA), to identify, assess and quantify the social implications of microgenerators is beyond the scope of this thesis and has therefore been left for recommended future research.

Nevertheless, since social consequences could be significant, the exclusion of which could either bias or render incomplete the outcomes of the CBA, the possible social significance of the three assessed microgenerators, such as on employment, empowerment, self-reliance, and human psychology are covered qualitatively in Chapter 7 and an attempt to include them is applied through the SMART in Chapter 8.

2.4 Cost-benefit analysis (CBA)

Cost-benefit analysis (CBA), the main tool or method for this thesis, is often referred to as 'efficiency benefit-cost analysis' (Campbell & Brown, 2003), 'social cost-benefit analysis' (Brent, 1996; Campbell *et al.*, 2003), 'environmental cost-benefit analysis' (Perman *et al.*, 2003), or simply as cost-benefit analysis (Boardman *et al.*, 2006). This variation could possibly be due to where the author wishes the relative focus of his/her assessment to be. However, 'qualitative cost-benefit analysis' could be argued to be a more suitable heading if not all the costs and benefits of a particular policy, programme or project (PPP) could be monetised, and cost-effective analysis (CEA) would be a better alternative if the major benefits of compared policies,

programmes, projects or technologies that have a similar objective cannot be monetised (Boardman *et al.*, 2006). In this thesis the term ‘cost-benefit analysis’ will be used throughout, despite the fact that much of the focus will be on accounting for the environmental implications of the assessed microgenerators, and despite the fact that a significant and unavoidable ‘qualitative’ assessment of costs and benefits is presented.

CBA is a systematic, quantitative method for the evaluation of proposed public or private expenditures or regulatory activities with the goal of identifying the alternative that will make the most efficient use of society’s scarce resources in promoting social objectives which maximises net social benefits (Campen, 1986). In other words, CBA aims to maximise the present value of all benefits less that of costs of policies, programmes, or projects (PPP) under consideration subject to specified constraints (Brent, 1996).

The underlying theoretical basis for CBA lies in the concept of Pareto efficiency, where CBA could then be thought of as providing a framework for measuring efficiency (Boardman *et al.*, 2006). A Pareto efficient allocation of goods occurs only when there is no alternative allocation that can be found which makes at least one person better off without making anyone else worse off. If alternative allocations can be found then ‘Pareto improvements’ are possible by making some people better off without making others worse off. This is the fundamental link between net benefits and Pareto efficiency; “If a policy has positive net benefits, then it is possible to find a set of transfers that makes at least one person better off without making anyone else worse off” (Boardman *et al.*, 2006). This welfare criteria leads to the underlying assumption that social welfare depends on the individual welfare of the members of society and that an individual’s welfare is best judged by that particular individual as measured through the willingness to pay (WTP) criterion;

“If at least one individual believes his/her welfare is greater with alternative A than with alternative B, and no individual believes that his/her welfare is less (i.e. one person has a higher WTP for A than for B and no person has a higher WTP for B than for A), then it is legitimate to conclude that A makes a greater contribution to social welfare than does B, i.e. it is Pareto superior and a Pareto improvement is possible...” (Campen, 1986).

The implications of the above mentioned Pareto efficiency rule seem to suggest that only the proposals that yield positive benefits, after completely compensating persons who may have faced costs, should be given the go-ahead or adopted. The applicability of this criterion however is near impossible in the real world due to several reasons. The first reason is that the informational burdens required to actually measure the benefits and costs of persons individually, let alone measuring the aggregate costs and benefits, would be immense and too costly. Secondly, even if the information barrier is overcome, the administrative costs of actually making the necessary transfers would potentially be very high and there would be strong incentive for people to find ways to overstate their costs and understate their benefits. Lastly, it would be very difficult to operate a compensation payment system which does not distort the investment and work behaviour of households (Boardman *et al.*, 2006).

Therefore, CBA uses an alternative decision-rule known as the Kaldor-Hicks criterion⁶ (or the ‘potential compensation criterion’) which considerably relaxes the Pareto efficiency rule by stating that ‘a proposal should be adopted if and only if those who will gain could fully compensate those who will lose and still be better off’ (Boardman *et al.*, 2006). The main difference therefore between Pareto efficiency and the Kaldor-Hicks criterion is that all that is required under the latter is the knowledge that the proposal has positive net benefits, of which in principle a part could be transferred to compensate those who lose from the proposal, without any transfer however actually taking place. Besides the feasibility or the applicability of Kaldor-Hicks criterion, two other mentioned justifications for relying on this criterion are generally presented. The first justification indicates that the ‘positive net benefits’ of proposals maximise the aggregate wealth of society which in turn can assist those who are worse off or less wealthy. Secondly, different proposals will undoubtedly have different winners and losers and therefore costs and benefits will tend to average out and each person is likely to realise a net benefit from a collection of proposals (Boardman *et al.*, 2006).

2.4.1 The CBA process

The methodology of CBA is relatively well established in the literature and would more or less follow the rationale behind the eight steps presented in Figure 2.5 and individually detailed in ensuing text. The CBA of the assessed microgenerators implemented in this thesis follows the general sequence of Figure 2.5.

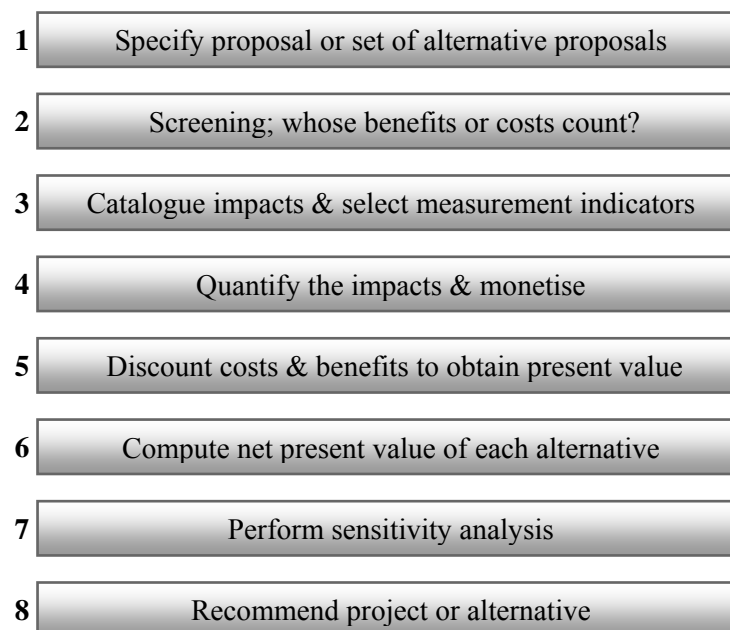


Figure 2-5 The Cost-Benefit Analysis Process
(Source: Boardman *et al.*, 2006)

⁶ The naming of the Kaldor-Hicks criterion came about after the publication of “Welfare Propositions of Economics and Interpersonal Comparisons of Utility” by Nicholas Kaldor in the *Economic Journal* in 1939 and the publication of “The Valuation of the Social Income” by John R. Hicks in the journal ‘*Economica*’ in 1940 (Boardman *et al.*, 2006).

2.4.1.1 Specify proposal

CBA begins with specifying the project or projects (or policy, program or technology) at hand, indicating the project that needs analysis relative to some pre-defined status quo, or indicating the two or more projects that would be economically assessed relative to one another. In the context of this analysis, a CBA would be implemented on individual microgenerators independently.

2.4.1.2 Screening

The second step in CBA, as indicated in Figure 2.5, is ‘screening whose benefits and costs count?’ CBA is used to take a ‘society-wide’ perspective where all the benefits and costs should be included, consisting of private and social, direct and indirect, tangible and intangible (i.e. not traded in a market place). In other words, CBA seeks to account for all costs and benefits regardless to whom they accrue and whether or not they are accounted for in the financial account (Campen, 1986). This is in contrast to financial appraisal where a private perspective (e.g. householder or firm) is held and only private benefits and costs are measured through market prices (see Section 2.4.2). Moreover, some contention may arise depending on the proposal at hand concerning the geographical extent of a CBA, i.e. whether local, national, regional or global impacts should be assessed (Boardman *et al.*, 2006). However, given the many regional (e.g. acid rain) and global (e.g. climate change) dimensions of current day environmental problems, CBA should encompass all costs and benefits, including therefore the global ones in order to be complete. Climate change impacts for example are accounted for in the CBA implemented in this thesis.

2.4.1.3 Cataloguing impacts and selecting indicators

The third indicated step in CBA is to list the physical impacts (both inputs and outputs) of the proposal as either costs or benefits and select their respective measurement indicators (Boardman *et al.*, 2006). An important caveat in CBA is that it is interested only in impacts that affect the utility of individuals, meaning that only when human beings have the relevant knowledge and information to make rational valuations will impacts be accounted for, while impacts without any value to human beings are excluded (Boardman *et al.*, 2006). Even the intrinsic value (the value of something in and of itself alone) of any regarded species of flora or fauna, for example, is valued through what a person would be willing-to-pay (WTP) to preserve that species.

2.4.1.4 Quantifying impacts and monetising

The fourth step of CBA is to quantify all impacts of the proposal in each time period and monetise those impacts. This would undoubtedly include the prediction of impacts into the future as proposals’ lifetime would, more times than not, extend years if not decades into the future. Much of the uncertainty in CBA lies in trying to predict the costs and benefits that occur in the future.

Monetising the identified and physically quantified impacts could be the more contentious part of a CBA. The value of an output in CBA is measured via the

willingness-to-pay (WTP) for that output. WTP is the conceptual standard for measuring changes in welfare or utility. In other words, an individual's welfare or utility can be expressed via her or his WTP for goods or services or some amenity or other. Where competitive markets exist and function properly, WTP can be determined from the appropriate market demand curve, as expressed in Figure 2.6.

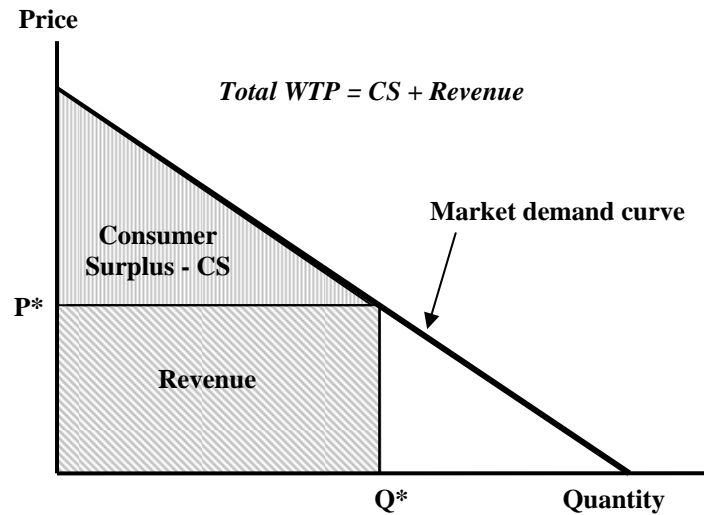


Figure 2-6 WTP as a measure of total benefits

Figure 2.6 shows a market demand curve (here assumed to be linear) for a certain product, where quantity Q^* of that product is purchased at price P^* . The area under the market demand curve represents the aggregate willingness-to-pay values of all individuals in a society. Consumers pay the market equilibrium price P^*Q^* for the product, however there are some consumers who would have been willing to pay more for the product – represented by the area defined as the consumer surplus. Similarly the consumer surplus, for an individual, is the difference between what one is willing to pay and what one has to pay for a product or service (Brent, 1996). Therefore the correct measure of ‘benefits’ in a CBA is the willingness-to-pay measure, while using the market revenues as proxy for benefits will undoubtedly lead to an underestimation as it leaves out the CS.

The demand function expresses the quantity demanded as a function of the main determinants of demand such as price of product, price of other products, income, tastes, and so forth. When the price of a product changes and a change in the quantities consumed follows, the change can be directly observed or recorded and a subsequent estimate of the price elasticity of demand is calculated. The price elasticity of demand, ϵ_d , is defined as the percentage change in quantity that results in a unit or 1% change in price, as expressed in Equation 2-3.

$$\epsilon_d = \left(\frac{\Delta Q}{\Delta P} \right) \left(\frac{P^*}{Q^*} \right) \quad 2-3$$

In order to calculate the ‘value’ of electricity and hot water, the price elasticity of demand is used in this thesis, constrained by several necessary assumptions, to determine the slope of the demand curve at a given price and quantity combination. Chapter 5 attempts to construct demand functions for electricity and hot water, and illicit values or WTP for these energy couriers. No such approach has been identified in the literature as applied on renewable energy systems in a CBA, given that it is always easier to opt for the displaced price of the energy courier (i.e., electricity, oil, or natural gas) as a conservative estimate for value, leaving out the contentious calculation of the CS.

Similarly, properly functioning markets could be lacking for environmental externalities as production (or consumption) of certain products or services have effects on third parties that are completely uninvolved in either the production or the consumption of those products or services (Boardman *et al.*, 2006). Figure 2.7 underlines the problem of externalities (or in this case the cost of environmental degradation). In a competitive market place, most private industries or firms will produce output at Q_1P_1 , where marginal private cost is equal to marginal private benefits (for simplification marginal private benefits and marginal social benefits are considered here the same and a linear model is assumed). However, when production leads to environmental externalities such as health-related or ecosystem damage caused by air pollution (e.g. in the form of sulphur dioxide or greenhouse gases) or water pollution (e.g. in the form of untreated chemical effluents dispersed in rivers), there would be unaccounted for costs (marginal damage costs - MD) incurred by society, shown by the difference between the marginal social costs (MSC) and the marginal private costs (MPC) in Figure 2.7.

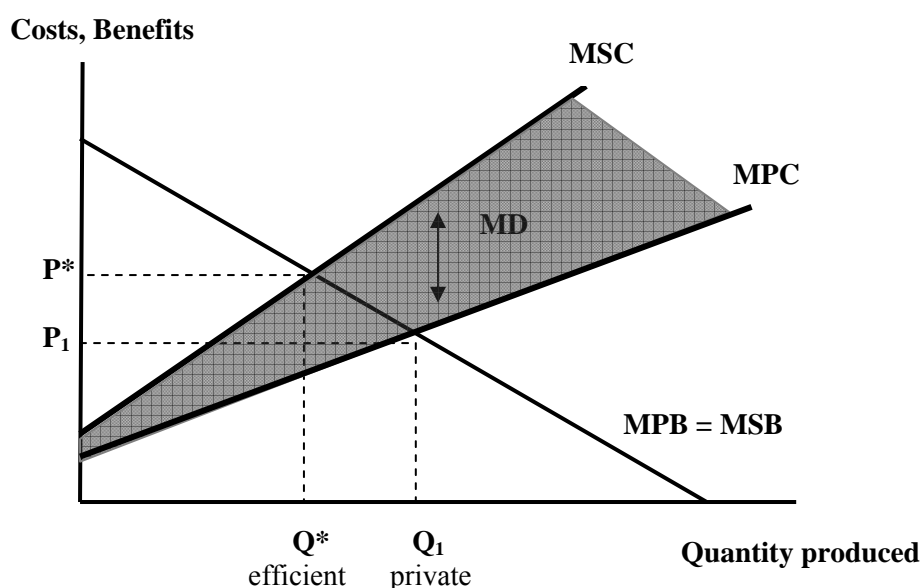


Figure 2-7 Marginal social costs and marginal private costs

Quantifying environmental externalities (i.e. marginal damage costs) or alternatively quantifying the ‘value’ of public goods (like access to clean air) is not a straightforward matter and often has not only measurement difficulties but also ethical

considerations, for example, placing a monetised value on risks to human life, an endangered species, or weighing future generations less than current ones.

Several studies use environmental economic techniques used to quantify environmental externalities⁷. The most notable is the ExternE project which commenced in 1991 as the European part (European Commission) of a collaboration with the US Department of Energy in order to systematically evaluate the external costs of a wide range of different fuel cycles (Chapter 3). It is mostly the values from the ExternE publications (and its update; the New Energy Externality Developments for Sustainability - *NEEDS*) that are used in the present CBA of the microgenerators.

Chapter 3 discusses in detail the ExternE (and *NEEDS*) methodology adopted to account for environmental costs and benefits attributed to the assessed microgenerators. This is done through the ‘integrated appraisal’ framework’ by specifically combining LCA outputs with values from environmental risk assessment (ERA) studies.

2.4.1.5 The social rate of discounting and present value

The fifth step in a CBA is to ‘discount costs and benefits to obtain the present value’ as illustrated in Figure. 2.5. The discount rate is a highly influential parameter in the calculation of the present values of costs and benefits that may occur in the future, as in the case of the benefits (and costs to a lesser extent) of the assessed microgenerators. Individuals reveal their time preference rate through market decisions, such as lending and borrowing, through the real interest rate on such activities (OXERA, 2002). However, for society as a whole, it is the willingness of society to trade consumption now for later over longer periods of time which defines the ‘social rate of time preference’. For CBA, it is this ‘social rate of time preference’ which should be applied in the analysis, given that, as mentioned before, it is the society-wide costs and benefits that are of interest. This section explains the parameters making up the ‘social rate of time preference’, briefly discussing the existing and often conflicting arguments for the parameter’s values. It is not the objective of this section to lend support to any one of those presented arguments, yet in the end the official UK government view on the values of the parameters would be more or less adopted. However, it is important to at least present the rationale for using these values and the objections to them.

According to Pearce and Turner (1990), the rationale for discounting lies in interest rates. One pound in Year 1 would accumulate to £1(1 + r) in Year 2 if the interest rate is ‘r’. Therefore, £X in Year 2 would be worth (present value) £X/(1+r)² for us today. The present value of costs and benefits occurring at time t are conventionally discounted as shown in Equation 2-4 (OXERA, 2002).

$$PV(B_t) = \frac{B_t}{(1+s)^t} \quad \text{2-4}$$

⁷ These techniques are well documented in most environmental economics textbooks, and therefore only a brief description of each is provided in Appendix 2.

Where ‘PV’ refers to the present value, ‘B’ is net benefit, t is time, and s* is the social time preference rate. It can be deduced that the discount factor (d_t), or the ‘social weight being applied to benefits and costs at different points in time’, is as shown in Equation 2-5 (OXERA, 2002).

$$d_t = \frac{1}{(1 + s)^t} \quad 2-5$$

The discount rate and the subsequent discount factor are decisive in measuring the value of future benefits or costs in present terms. For example, employing a 2% discount rate would yield approximately £610 of present worth value for a £1000 in 25 years time, while it yields a present worth of only about £146 under an 8% discount rate.

Employing the accurate discount rate (or discount rates) is fundamental for CBA. However, discounting is subject to different views held by economic practitioners. The selection of the appropriate social discount rate (i.e., the social rate of time preference) is rather more of a subjective choice than a concrete science, as shall be discussed, and is bound by various philosophical and economic judgments and predictions of the future state of the economy - among other parameters.

Economists observe that consumers, by holding a positive rate of time preference and producers, through the opportunity cost of capital, treat the future as less important than the present (Hanley & Spash, 1993). More specifically, people will prefer benefits now rather than later due to the following (Pearce *et al.*, 1989);

- *There is positive capital productivity, where output is generated from capital through time;*
- *Even supposing a zero capital productivity, people display ‘impatience’, i.e., they have time preference;*
- *There is a ‘risk of death argument’, which can be included in the ‘impatience’ category by dividing ‘impatience’ into ‘pure impatience’ or ‘pure myopia’ and ‘risk of death impatience’;*
- *There is the ‘risk and uncertainty’ argument of discounting, that can also be added to the ‘impatience’ argument’, that benefits in year 2, or 3 or 4 and so forth would actually be there;*
- *If we expect the future to be better-off than us, as we do, then there is diminishing marginal utility, i.e., the utility attained from £1 in the future is less than the utility attained from that one-pound today.*

The arguments for discounting above could be accurately observed through the Ramsey Equation and its breakdown, shown in Equation 2-6.

$$\text{Ramsey Equation; } S(t) = \rho + \mu g(t) \quad 2-6$$

The social rate of time preference, $s(t)$, is equal to the rate at which individuals discount future utility or well-being (ρ), plus the multiplied elasticity of marginal utility (μ) and the rate of growth of consumption per capita at time ($g(t)$).

The first element on the right hand side of Equation 2-6, ρ , is comprised of two elements; the ‘rate of pure time preference’ (δ) and catastrophe risk (L) through the relationship shown in Equation 2-7 (OXERA, 2002).

$$\rho = \delta - \dot{L} \quad 2-7$$

The ‘rate of pure time preference’ (δ) has been debated extensively in the literature, and is often said to represent discounting for impatience or myopia, with many authors considering discounting according to δ as “ethically indefensible” (Cline, 1999). Table 2.2 lists several criticisms of a positive ‘rate of pure time preference’ by prominent economists.

Author	Statements against a positive pure time preference
Pigou, A. C.	Pure time preference implies our telescopic faculty is defective
Harrod, R. F.	Pure time preference is a polite expression for rapacity and the conquest of reason by passion.
Koopmans, T. C.	There should be an ethical preference for neutrality as between the welfare of different generations (yet he saw this as unacceptable because it leads to excessively high interest rates)
Robert Solow	In solemn conclave assembled, so to speak, we ought to act as if the social rate of time preference were zero.

Table 2.2 Criticisms of positive discounting
(Source: Arrow, 1999)

The Stern Review (2006) adopts a value of δ of almost zero or 0.1%, in addition to strongly making the case against opting for higher δ values, given the change of human extinction probabilities in climate change economics by using alternative values (Stern, 2006). Adopting a value of 1.5% for δ , for example, will make the probability of human extinction to be ‘as high as 78%’ by the end of the century (Stern, 2006). However, considering δ as zero also leads to impossibly high saving rates by “justifying the condemnation to misery of successive generations in the name of benefiting later generations” (OXERA, 2002). Arrow (1999) explains this statement in the following way;

“Imagine initially that output consists of a constant stream of completely perishable goods. There can be no investment by definition. Now imagine that an investment opportunity occurs, available only to the first generation. For each unit sacrificed by them, a perpetual stream of α per unit time is generated. Each unit sacrificed would yield a finite utility loss to the first generation, but to compensate, there would be a gain, however small, to each of an infinity of generations. Thus, any sacrifice by the first generation is good. We cannot say that the first generation should sacrifice everything (marginal utility approaches infinity as consumption approaches zero), but the logic above suggest quite a lot – just short of the entire income. This implication is unacceptable” (Arrow, 1999).

Nordhaus (1999) supports Arrow's argument that it would be too costly to lower the pure rate of time preference from 3% to 0%, or even 1%, requiring high-savings from the current generation as a means of attaining a distant environmental objective (Nordhaus, 1999). Nordhaus calculates that the net global saving rate will jump from 8.1% of net global product for the 3% discount rate to 17.7% and 24.3% of output for the 1% and 0% pure rates of times preference, respectively (Nordhaus, 1999).

Nevertheless, the literature suggests a very low value for δ in the range of 0.0-0.5, as quoted by the HM Green Book (2003), OXERA (2002), Dasgupta (2006) and, as aforementioned, the Stern Review (2006). For while it is true that individuals exhibit impatience (utility preferred now to later), 'it is not necessarily the case that society as a whole either does or should exhibit such impatience' (Perman *et al.*, 2003).

\dot{L} on the other hand is the rate of growth of life chances. It is negative due to the fact that if life chances get worse through time, then this makes for a higher rate of time preference, whereas if they get better then this argues for a lower rate of time preference (Pearce & Ulph, 1999). \dot{L} has been defined mainly in two alternative ways. The first is for an individual and it is the risk of that individual's death (and aggregation of risk of death for individuals across society), which justifies discounting future streams of consumption. The second, as cited by Pearce and Ulph (1999), is focused on the 'life chances of whole generations'. It is calculated by indicating the proportion of a generation that dies each year.

OXERA (2002) indicates the projected and recent death rates in the UK (Table 2.3), and accordingly estimates that 'changing life chances' (\dot{L}) is 1.1%, falling to 1% in the near future.

Year	Deaths per Capita	% of population dying each year
1991	0.0111	1.11%
2000	0.0102	1.02%
2011	0.00984	0.98%
2021	0.00999	1.00%

Table 2.3 UK death rates
(Source: OXERA, 2002)

Similarly, The Green Book adopts a value of \dot{L} between 1 and 1.2. OXERA (2002) and HM Green Book (2003) suggest that the value of welfare/well-being (ρ) is between 1.0 to 1.6 and 1.5, respectively.

The second part of the Ramsey Equation commences with the elasticity of marginal utility of consumption (μ). The marginal utility of consumption is the change of utility over the change of consumption, and this is assumed to be positive yet decreasing in consumption (diminishing marginal utility). Formally this entails the logic of Equation 2-8 (Pearce *et al.*, 1999).

$$\frac{dU}{dC} \Rightarrow U'(C) = \frac{dU}{dC} > 0 \rightarrow \text{but} \rightarrow U''(C) = \frac{d^2U}{dC^2} < 0 \quad 2-8$$

The value of μ could be retrieved by either observing how individuals wish to transfer consumption across time (individual saving behaviour), or by seeing society's judgement about how 'we should transfer consumption across people at different times' (Pearce *et al.*, 1999). The Stern Review adopts a value for μ of 1, or near 1. Pearce and Ulph (1999) adopt a value of μ equal to one, yet indicate a value specifically for the UK in the range of 0.8-0.9. Other studies quote a value of μ of 0.8 (Blundell *et al.*, 1994), or 'just below or just above one' (Cowell & Gardiner, 1999). OXERA (2002) adopts overall values of μ between 0.8 and 1.1, while HM Green Book (2003) adopts the value of μ to be 1 (from a quoted range between 0.7 and 1.5).

This near-unity value is not unchallenged by serious criticisms, particularly from Dasgupta (2006), who argues that μ should be between 2-4, due to the fact that a value of 1 means that the distribution of well being among people does not matter and that the present generation ought to spend a lot of money on future generations even if the latter are expected to be better off. Dasgupta (2006) gives an example of setting the pure rate of time preference, δ , at 0.1 as the Stern Review advocates, and which Dasgupta concurs with, and the marginal utility equal to 1 in a 'constant population, deterministic economy that experiences no technological change'. If the social rate of return on investment is 4% argues Dasgupta (2006), then the current generation in the model ought to save a full 97.5% of its aggregate output for the future, an absurd predicament given that the UK currently (as of 2006), for example, saves only 15% of GDP. Increasing the μ would entail a greater sensitivity to risk and inequality in consumption (Dasgupta, 2006).

The final parameter in the Ramsey equation is the rate of growth of consumption, $g(t)$. Table 2.4 illustrates the percentage annual growth in Gross Domestic Product (GDP) per capita in the UK over varying times spans.

Period	Average annual growth in GDP per capita, (%)	Period	Average annual growth in GDP per capita, (%)
1500-1820	0.27	1973-1998	1.79
1820-1870	1.26	1500-1998	0.65
1870-1913	1.01	1820-1998	1.35
1913-1950	0.92	1870-1998	1.39
1950-1973	2.44	1950-1998	2.10

Table 2.4 Percentage per-annum growth in GDP per capita in the UK
(Source: OXERA 2002)

Table 2.4 covers 100-180 years of data and suggests that $g(t)$ has a value between 1.3 and 1.6 (OXERA, 2002).

The values of each component of the Ramsey equation elicited from the above-cited literature pertained to the UK context are summarised in Table 2.5. They lead to a social discount rate of between 2.4% and 3.9%.

Variable	Pearce and Ulph, 1999 (%)	OXERA 2002 (%)	The Green Book 2003 (%) ⁸
δ	0 – 0.5	0.0 - 0.5	0 – 0.5
\dot{L}	0 – 1.2	1.0 - 1.1	1 – 1.2
μ	0.7 – 1.5	0.8 - 1.1	0.7 – 1.5
$g(t)$	1.3 – 2.2	1.3 – 1.6	2
$S(t)$	0.9- 5.0	2.0 – 3.9	3.5
Best estimate $S(t)$	2.4	2.4 - 3.3 (2.7%)	3.5

Table 2.5 **Summary of estimates of the discount rate and its components**

As can be derived from the arguments above, disagreement occurs over the choice of the discount rate, including the parameters of ‘pure time preference’, ‘marginal utility of capital’ and ‘economic growth’ levels (IPCC, 1996). The relative agreement in what affects the discount rate (regarded here as the dependent factor) is met with disagreement as to the values of these independent parameters. A survey of empirical literature implemented by Frederick *et al.* (2002) showed a huge difference between assumed discount rates, ranging from negative to infinite (∞) values, depending on the study (Frederick *et al.* 2002). Therefore, large variability in discount rate estimations exist, and many of the rates obtained, as noted by Frederick *et al.* (2002), are abnormally high.⁹

Broadly, there are two alternative approaches adopted for the selection of discount rates. The first is the prescriptive approach (denoting the social rate of time preference- SRTP - approach) and the descriptive approach (denoting the use of capital return for discounting or the use of optimization models that apply a pure rate of time preference of 3% or more). Caution should be taken in the terminology as some authors believe the terminology misleads a reader into thinking that one is ‘hypothetical’ or ‘normative’ while the other is ‘actual’ or ‘positive’, when that is not the case (Cline, 1999).

The prescriptive view perceives that the market rate of interest offers a poor indicator of the marginal trade-offs to society, because of market imperfections and suboptimal tax (and often expenditure) policy and due to constraints on policy, specifically the difficulty in making transfers to future generations (IPCC, 1996). The prescriptive approach arrives to the following conclusions;

“Decisions on discount rates should be derived from ethical considerations, reflecting society’s views concerning trade-offs of consumption across generations. Because of practical limits on the feasibility of intergenerational transfers, and in the absence of optimal tax policy, the SRTP will in general fall below the producer rate of interest. However, if a climate change mitigation project would displace private investment, and returns to both projects accrue to the same generation, then it is appropriate to

⁸ These estimates by the Green Book are for the first 30 years only.

⁹ The work here refers to the Frederick *et al.* (2002) study for an understanding and critic of these high discount rates. The literature review was indicated herein solely to reveal that indicating the discount ‘is not something we measure; it is something we choose’ (Hanley *et al.*, 1993), and is not indicated to critic, justify or refute these predominately high rates.

use the opportunity costs of capital...Only after doing this will it be appropriate to use the social rate of time preference to discount consumption” (IPCC, 1996).

Commonly, the prescriptive view indicates an effective discount rate of 2 - 3%, constituted of an almost zero ‘pure time reference’, 1 - 2% consumption growth and an elasticity of marginal utility of 1.5 (IPCC, 1996), as calculated via the Ramsey formula (see above).

Advocates of the descriptive approach alternatively claim that mitigation expenditures displace other forms of investment, and thereby they claim that decision-makers ought to make decisions that increase total consumption, i.e., if return on mitigation investment lies below that of other investments, then choosing other investments would make current and future generation better off. Therefore, the descriptive approach advocates the inferring of the social discount rate directly from current rates of return and growth rates (IPCC, 1996). However this is not an easy inference, as then the question of which rate of return to adopt is confronted by economists. For example, large companies in the US had a real return to investment of 7% between 1926 and 1990 (a rate recommended for CBA by the US Office of Management and Budget), yet corporate income taxes of 35% indicated that the pre-corporate-tax return to private investment is closer to 11% (Newell & Pizer, 2004).

There are four additional arguments as to why using market prices (interest), like the descriptive approach endorses, is inappropriate (Hepburn, 2007)

- *Market imperfections; Market prices often give a misleading signal of value as a result of a sub-optimum distribution of income or because of other distortions in the economy, such as externalities, government taxation, imperfect information and the exercise of market power. Under such conditions, market prices do not reflect the “shadow price”, or the true social opportunity cost of the resource;*
- *Super-responsibility; It is sometimes argued that the government has a responsibility to both current and future generations. As markets only reveal the preferences of the current generation, the government should not rely solely on market information;*
- *Dual-role; The members of the present generation in their political role may be more concerned about future generations than their day-to-day activities on current markets would reveal;*
- *Isolation argument; controversially it is said that individuals may be willing to join in a collective savings contract, even though they are unwilling to save as much in isolation.*

There is yet a third approach to discounting that tries to better cater for all the uncertainties involved, particularly when valuing the far off future. In specific, the science and economic implications of climate change are not perfectly certain, specifically as they are compounded by long time horizons. There are uncertainties with respect to technological progress¹⁰, economic growth rates, and so forth. One way to tackle this issue is that ‘when there is an uncertain discount rate, the correct discount rate for a particular time period, the certainty-equivalent discount rate, can be

¹⁰ Weitzman (1998) argues that, in the distant future there is uncertainty in the productivity of capital which is driven by the factors determining the marginal productivity of capital (capital accumulation, degree of diminishing returns, state of the environment, state of international relations...).

found by taking advantage of the discount factor, rather than the discount rate itself' (OXERA, 2002). In other words, 'uncertainty about future rates provides a strong generic rationale for using certainty-equivalent social interest rates that decline over time from around today's observable market values down to the smallest imaginable rates for the distant future' (Weitzman, 1999).

An example given by Hepburn (2007) illustrates the use of certainty-equivalent discounting. Table 2.6 presents discount factors for two discount rates (2% and 6%) under various Time categories. The average of those discount factors is called the 'certainty-equivalent discount factor', and working backwards we can determine the 'certainty-equivalent discount rate', which starts at 4% and declines asymptotically to 2% as time passes (Hepburn, 2007).

Time (years from Present)	1	10	50	100	200	400
Discount factor for 2% rate	0.98	0.82	0.37	0.14	0.02	0.00
Discount factor for 6% rate	0.94	0.56	0.05	0.00	0.00	0.00
Certainty-equivalent discount factor	0.96	0.69	0.21	0.07	0.01	0.00
Certainty-equivalent (average) discount rate	4.0%	3.8%	3.1%	2.7%	2.4%	2.2%

Table 2.6 Numerical Example of a declining certainty-equivalent discount rate
(Source: Hepburn, 2007)

The two assumptions in this example are that the discount rate is uncertain and persistent, so that the expected discount rate in one period is correlated with the discount rate in the previous period. If these assumptions hold, efficiency considerations require a declining social discount rate (Hepburn, 2007).

Thereby the 'certainty-equivalent discount rate for constructing discount factors is the harmonic mean of the discount factors and declines over time, falling at the limit to the lowest conceivable rate' (OXERA, 2002). In doing this, the values from scenarios with the low discount rates contribute more to the weighted average with time (OXERA, 2002).

The third view therefore adopts a declining discount rate approach, and for this the values of OXERA (2002) and the Green Book (2003) fit accordingly (and officially) through the schedule of Table 2.7.

Periods of Years	0 - 30	31 - 75	76 - 125	126 - 200	201 - 300	300 +
Discount rate	3.5%	3%	2.5%	2%	1.5%	1%

Table 2.7 Declining long-term discount rates
(Source: Green Book, 2003)

In summary, the literature review above indicates more or less three approaches; the prescriptionist approach, the descriptionist approach, and the declining rates approach.

All these approaches, as illustrated earlier, have their strong and weak arguments, and their varying implications, and yet neither argument is predominant in justifying the actual selection of discount rates. In the end the selection of the social discount rates will depend on ethical and philosophical views as well as opinions regarding

projections of how the world will look like in 50,100, 200 years time (in economic terms) among other parameters.

Based on the discussion above, the CBA implemented on the microgenerators in this thesis has opted for a default 3% discount rate¹¹, however alternative discount rates of 1.5% and 5% are also implemented in the sensitivity analysis to reflect more the prescriptionist views and the descriptionist views, respectively.

2.4.1.6 Computing net present value

The sixth step in CBA is to compute the net present value of each alternative under consideration. The net present value (NPV) of an alternative equals the difference between the present value of the benefits and the present value of the costs, as shown in Equation 2-9 (Boardman *et al.*, 2006).

$$NPV = -I + R \sum_{0}^T (1 + r)^{-t} \quad 2-9$$

Equation 2-9 sums up the CBA methodology, where $-I$ represents the initial investment costs, ' R ' the annual revenue, ' r ' the discount rate, and ' t ' the time frame involved. In essence, Equation 2-9 entails that costs in each year are deducted from benefits of that year, including environmental and/or non-market valued ones, discounted all by the discount factor, $(1+r)^{-t}$, to the net present terms (NPV), summed (\sum) and reduced by initial investment.

If one is comparing two or more alternatives, the decision to select one is based on the highest net present ratio (NPV). When selecting whether to proceed with one alternative only however, the criteria to go ahead is based on a NPV being at least 0, or a benefit-cost ratio (BC ratio) being at least 1. BC ratio is the ratio of expected benefits to every one unit of costs. Although the BC ratio and the positive NPV criteria guarantee that no project goes forth if benefits are less than costs, they do not guarantee efficiency however – as illustrated in Figure 2.8.

¹¹ Originally a 3.5% discount rate was used, however given that most of the damage values, such as the social cost of carbon, is valued with a 3% discount rate, the author has opted for the latter to avoid a discrepancy in the analysis. However this discrepancy cannot be avoided in the sensitivity analysis.

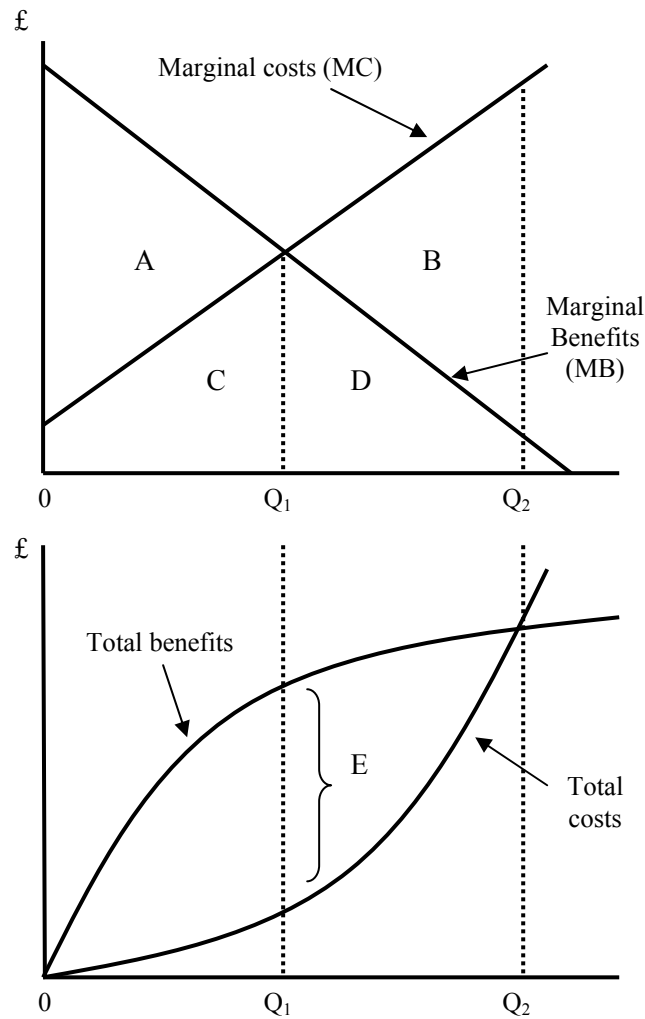


Figure 2-8 Benefit-cost analysis and efficiency
(Source: Tietenberg, 1996)

Efficiency is attained when marginal cost is equal to marginal benefits ($MC = MB$), i.e., at point Q_1 in Fig. 2.8. At Q_1 the total benefit exceeds total costs by the maximum amount of E (bottom graph). However, at Q_2 the net benefits are also zero as revealed via area A being equivalent to Area B at that point. Area B is net costs and Area A is net benefits, yet at Q_2 the net benefits are zero. This implies that average benefits are equal to average costs, and the total benefits are equal to total costs. Therefore, the benefit-cost ratio herein at Q_2 is also 1 (Tietenberg, 1996).

Therefore the positive net present value and the benefit-cost ratio criteria do not deliver on efficiency terms. This is important in the context of the CBA on microgenerators because, as shall be seen, cost-benefit analysis is undertaken on each microgenerator in absolute terms and not in relative terms. In other words, even if a microgenerator meets the criteria of a positive net present value and a benefit-cost ratio larger than (or equal to) one, there could be (and are indeed) cheaper ways to deliver energy or electricity on a levelised cost (i.e. pence/kWh) basis. This is shown in Chapter 8, where a cost-effective analysis (CEA) is presented and most electricity (and heat) generation sources are compared.

2.4.1.7 Sensitivity analysis

The 7th step in CBA is sensitivity analysis. Sensitivity analysis measures how sensitive the result of a cost-benefit analysis is to a change in one of the variables, which could be approached either via variable-by-variable that treats each variable separately, or through a scenario approach which treats variables in groups, particularly when there is interdependency of these variables (Zerbe & Dively 1994).

The variable-by-variable approach requires first the listing of all variables important for the analysis, followed by a range of possible alternative values (e.g. ‘most likely other value’, ‘optimistic’, or ‘pessimistic’) that could be used for the estimation of net present value – holding all other variables constant. The scenario approach is used when one or more variables are altered for each scenario in order to depict results through, for example, a minimum, mean, maximum criterion.

There are several drawbacks of sensitivity analysis. First, there are no clearly defined rules for choosing values for variables and second, particularly the variable by variable approach, sensitivity analysis overlooks possible interaction among the variables. These limitations make sensitivity analysis useful only for relatively ‘simple problems or for problems where rough accuracy is sufficient’ (Zerbe & Dively 1994).

In this thesis, the default CBA already contains several variations of the possible parameters, such as capital costs and expected output from the microgenerators, and additionally four approaches to environmental monetization are provided for. Other parameters, such as a change in environmental costs and benefits within each of the four approaches applied, and the discount rate are varied in the sensitivity analysis.

For the financial appraisal, various capital costs and energy outputs are provided for in the original appraisal; however alternative future energy prices and discount rates are implemented in the sensitivity analysis.

2.4.1.8 Recommendations

The final step of a CBA is to make a recommendation with respect to either the project being looking into, i.e., whether to proceed with the project or not, or indicate a better alternative between a set of similar projects.

With respect to the economic assessment of microgenerators, because CBA is involved in assessing the ‘social’ costs and benefits of installing any one of these systems, there are some potential benefits that the above-mentioned CBA process will not be able to capture. Most notably, most of the capital costs of microgenerators are becoming less expensive by the year through a well-documented process known as the ‘experience curve’ or ‘progress ratio’ (see chapter 7). This process indicates that with every doubling of global capacity of a certain system, there is an expected percentage reduction of the system’s costs. The less mature systems are, such as photovoltaic or microwind systems, the more pronounced the potential effect could be. Consequently if the CBA delivers negative results (i.e., the systems are

uneconomic) and the technologies are denied government support for example for installation, these future cost reductions (which could be considered a positive externality of production) will be less likely to occur or will occur in smaller measures or further into the future. In other words, the future also should play a part or be integrated in any CBA in a more dynamic manner, including benefits of investing now as opposed to later, as illustrated in Figure 2.9.

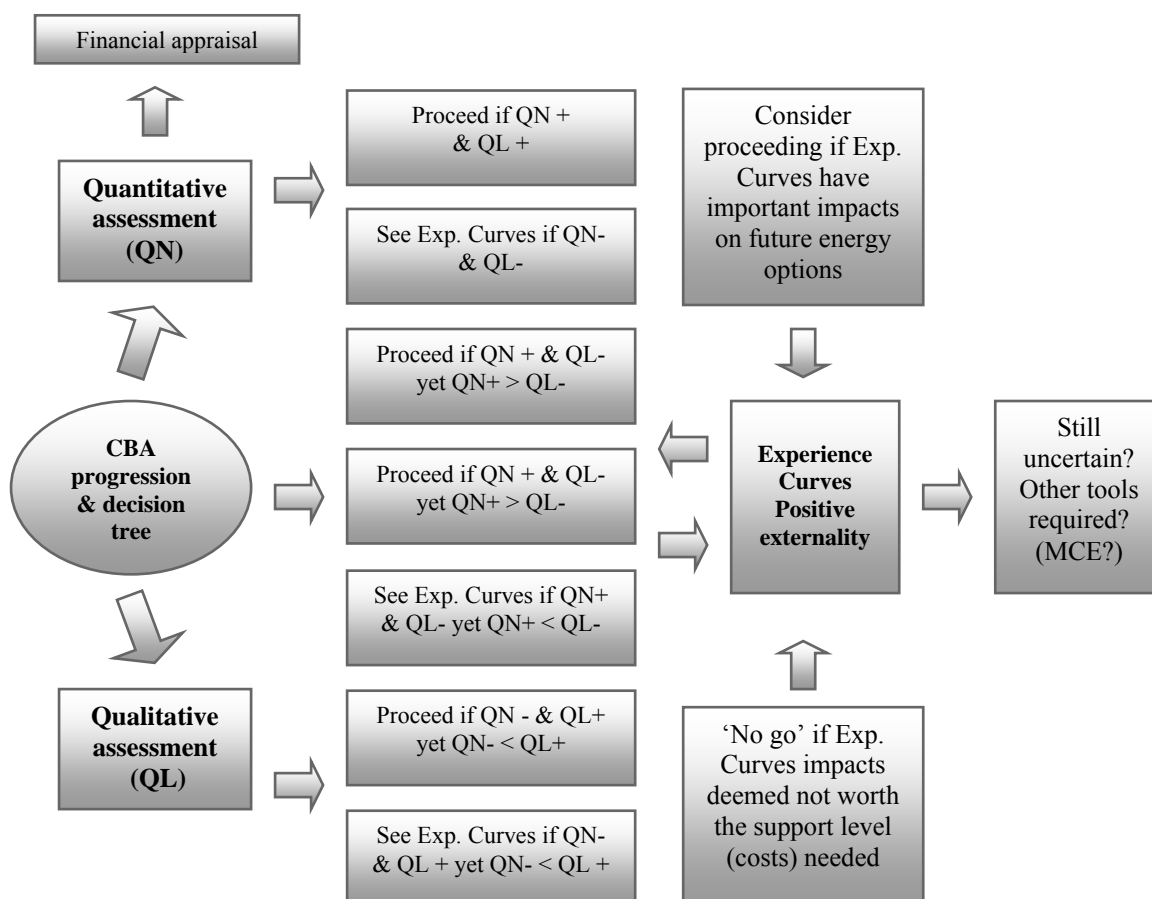


Figure 2-9 CBA progression and decision tree for the assessed microgenerators

Figure 2.9 could be considered the road map of this thesis. It demonstrates that a CBA is composed of a quantitative part, which was broadly described above, and a qualitative part. More times than not a CBA will include a qualitative assessment where project implications on such categories as, for example, psychology, political empowerment and so forth are difficult if not impossible to monetise even if the CBA practitioner is not subject to time and cost constraints. In other words, ‘not everything under the sun can be monetised’¹² and qualitative assessment will remain an important and integral part of CBA. For this reason, the assessment given will remain called cost-benefit analysis as opposed to qualitative cost-benefit analysis, as mentioned at the beginning of Section 2.4.

¹² Anonymous

Referring further to Fig 2.9, the decision to proceed with a project should be taken if (1) both the quantitative assessment (QN) and the qualitative assessment (QL) are positive, or (2) if the QN is positive while the QL is negative subject to the positive QN outweighing the negative QL, or (3) if the QN is negative yet the QL is positive subject to the latter outweighing the former. Whether or not a qualitative assessment (QL) outweighs the quantitative one is therefore a subjective judgment. Given our particular case of microgeneration, the CBA practitioner should also assess (as implemented in Chapter 7) the future implications of the current proposal, particularly if a decision *to proceed* or *not to proceed* cannot be made through the combined quantitative and qualitative assessment. If the decision would still not appear to be clear cut, as would be the case in this study, then the use of alternative decision-aiding tools, such as multicriteria evaluation (MCE), should be recommended. A simple multi-attribute rating technique (SMART) is applied in Chapter 8 in order to give an alternative perspective as to whether or not the assessed microgenerators are worth their cost.

In parallel, a financial appraisal is applied in Chapter 6, in order to show whether or not the required financial incentives are present at the individual private level to successfully support the assessed microgenerators.

2.4.2 Financial appraisal

It would be the UK householders whom will decide in the end whether or not to purchase any of the selected microgenerators if it makes financial sense to them alone. Financial appraisal (FA) is used to assess the costs and benefits of the microgenerators in terms of outlays and receipts accrued by a private entity (i.e. households) as measured through market prices (Brent, 1996). Environmental impacts are excluded therefore from FA, yet any transfer of income such as through taxes and/or subsidies (e.g. grants or feed-in tariffs) would be included. Therefore the FA of microgenerators would really follow a discounted cash flow approach where costs and benefits at each time period (t) would be estimated and discounted to the present to indicate the net present value (NPV).

In addition, the simple payback time would be used to indicate how quickly the incremental benefits that accrue from a technology (in this case a microgenerator) would 'pay back' the initial capital invested (Lumby & Jones, 2001). The simple payback method (PBM) is a procedure utilised to estimate the length of time it will take for a project to recoup its costs, without the application of interest rates. The method assumes that a given proposal will generate 'a stream of monies during its economic life, and, at some point in time, the total value of this stream will exactly equal its initial cost,' an equalization called the payback period expressed in Equation 2-10 (Rogers, 2001).

$$\text{Payback period} = \frac{C_o}{NAS} \quad \text{2-10}$$

C_0 is the initial cost of the project and NAS is the net annual savings or net cash flow that will recover the investment after the payback period.

Most uses of the PBM take a zero discount rate, and yet discounting could be incorporated in the Payback method, increasing or decreasing thus the payback period depending on whether the project has a net annual saving or net cost flow. Only the undiscounted payback indicator is implemented in the assessment of microgenerators, given that discounting is well represented in the NPV and BC ratio indicators.

Financial appraisal uses the market rate of interest (net of inflation) as a lower bound discount rate, and therefore indicates the real return that would be earned on a private sector investment. The actual ‘implicit’ discount rate may often be substantially higher than this however for household energy-related investment such as micro-generation, even up to 30% according to Watson *et al.* (2008). However, Watson *et al.* (2008) conclude that it is difficult to accurately identify discount rates for individual consumer investment decisions as it is unlikely that individuals use a discounted cash flow analysis. Therefore an alternative being the use of a company investment rate of 8% was used by Watson *et al.* (2008). This rate was also applied by EST *et al.* (2005).

In the financial appraisal of microgenerators applied in this thesis, a lower discount rate of 5% is used with sensitivity analysis alternatives of 3% and 8%. The author believes that since the microgenerators are being sold, although in small numbers, in the UK, other factors besides rational economics must be at play, factors which are discussed qualitatively in Chapter 7.

2.5 Multicriteria evaluation (MCE)

Multicriteria evaluation (MCE) is a widely applied method to compare and rank options by a large number of criteria, and it is widely used in electricity generation planning and energy policy design (Madlener & Stagl, 2005).

A simple method of MCE is applied in this study in order to assist in deciding whether or not the assessed microgenerators should be given the ‘go-ahead’ and advocated, or should be shelved. This is done due to the fact that the CBA contained several qualitative parameters that could not be monetized. A simple multi-attribute ranking technique (SMART) is implemented in Chapter 8, following Goodwin and Wright (2009). The methodology and/or process of SMART are described in Chapter 8.

3 Quantifying the Environmental Implications of Microgenerators; Four Alternative Approaches

3.1 Introduction

Given the ‘integrated’ nature of the assessment implemented in this thesis, the results or outcomes of the energy analysis with respect to the assessed microgenerators provides for both the LCA, which in turn feeds back to the energy analysis to calculate such parameters as energy gain ratios for example, and the CBA. Given that social implications are discussed in Chapters 7 and 8 within the context of the CBA and alternative decision-aiding tools (SMART), this simple configuration is shown in Figure 3.1.

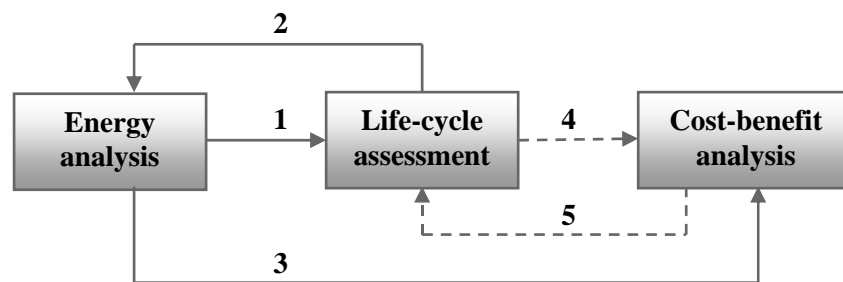


Figure 3-1 Integrated appraisal procedure

The main objective and contribution of this thesis is to apply a CBA on the microgenerators (see Figures 1.1 and 1.2). To do this, the ability of incorporating the energy analysis and the LCA outputs into CBA is required, which would also strengthen the ‘integrated’ nature of the appraisal.

The linkages between energy analysis and LCA presented in Figure 3.1 could be clarified directly through solid paths 1 and 2. Specifically for the microgenerators, energy analysis would indicate how much ‘renewable’ energy these systems shall produce over their lifetimes. This would constitute the environmental benefits of the ‘use’ phase of the LCA (in terms of the life-cycle avoided environmental impacts of displaced electricity or natural gas for example). The LCA in turn would indicate the amount of energy it took, or the gross energy requirements, to produce or manufacture these systems up to the ‘point of interest’ or use; allowing therefore for an energy-related justification (or the lack of) for these systems, as well as a comparison of energy performance with the alternative and displaced energy courier, such as electricity, oil, or natural gas. The accord between energy analysis and LCA cannot be said to extend, however, to CBA.

With respect to energy analysis and CBA, the association can be considered one-sided as shown through solid path 3 in Figure 3.1. Energy outputs of the microgenerators, as provided for through the energy analysis, are fundamental inputs into the CBA of Chapter 5 (and the financial appraisal of Chapter 6), accounting for the central benefits of those systems. The energy outputs of the assessed microgenerators are presented in Chapter 4.

On the other hand, the association between LCA and CBA, as expressed through the dashed paths 4 and 5 in Figure 3.1, are not as simple to associate together. The linkages between LCA and CBA would have been as that between energy analysis and CBA if the result or outcome of LCA could simply be valued monetarily and included. Yet this is only possible with significant uncertainties and assumptions due to the fact that the underlying compatibility between LCA and CBA, particularly their paradigms, scopes, goals and objectives, could be potentially very different.

The joining of LCA outputs into CBA within the context of the assessed microgenerators is one of the main contributions of this thesis, again beyond implementing a CBA (and FA) on these same systems as an objective in itself. Originally, the Eco-indicator 95 LCIA method has been used by the SERT (including the author) at the University of Bath, and Allen *et al.* (2008a and 2009) and Hammond *et al.* (2009) to bridge these two methods, however alternative and more accurate and/or compatible methods have been identified and are implemented in this study.

This chapter focuses first on the Eco-Indicator 95 (EI-95) and its output as used in Allen *et al.* (2008a and 2009) and Hammond *et al.* (2009). As mentioned before, the EI-95 has been used by the SERT (including the author) as the main LCIA method (up to mid-2009). Notwithstanding that this method has now been superseded, the strengths and weaknesses of having used outputs from this method as inputs into the CBA of the here-selected microgenerators, has been the starting point of assessing the compatibility of LCA and CBA. From the EI-95, the author presents alternative methods (including LCIA methods) that are arguably better suited for CBA, strengthening the inter-linkages of the ‘integrated appraisal’.

3.2 Eco-indicator 95 (EI-95); a mid-point approach

As mentioned in Chapter 2.1.2, the third phase of LCA is the LCIA. It is applied in order to assess the environmental significance of a product’s system life-cycle inventory, through the selection and definition of impact categories, classification, characterization, and optionally normalization, grouping and weighting.

In general, LCIA accounts for several impact categories, namely: climate change, stratospheric ozone depletion, photo-oxidant formation (smog), eutrophication, acidification, and so forth that can be grouped into three broad ‘areas of protection’ (AoP) involving (1) resource use, (2) human health consequences, and (3) ecological consequences (Pennington *et al.*, 2004). The LCIA involves the selection of impact categories, category indicators, the assignment of life-cycle inventory results to the impact category (classification), and the calculation of category indicator results (characterization). However, there are inherent difficulties in selecting impact categories and there is a lack of standardization to this regard (Reap *et al.*, 2008). Two main modelling approaches to LCIA developed in due course. These are LCIA models which either rely on mid-point impact indicators or on end-point impact indicators. Midpoint indicators are considered to be points in the cause-effect chain of a particular impact category, between stressors and endpoints, and midpoint characterization factors can be calculated to reflect the relative importance of an emission or extraction in a life-cycle inventory (UNEP, 2003). Historically, mid-point approaches have dominated the field of LCA through the use of several methods such

as the EI-95, the method outlined next and employed in Allen *et al.* (2008a, 2008c, and 2009) and Hammond *et al.* (2009). On the other hand, end-points approaches focus on those elements of an environmental mechanism which are in themselves of value to society, such as damage to human health, ecosystem quality and resources (UNEP, 2003). The Eco-indicator 99 (EI-99) and the EPS 2000 are prominent examples of end-point approaches outlined in Sections 3.3.3 and 3.3.4.

Figure 3.2 illustrates the structure of the EI-95, beginning with the effects or emissions, characterized then into nine impact categories, and evaluated and weighted using the ‘distance to target principle’ to achieve an Eco-indicator result.

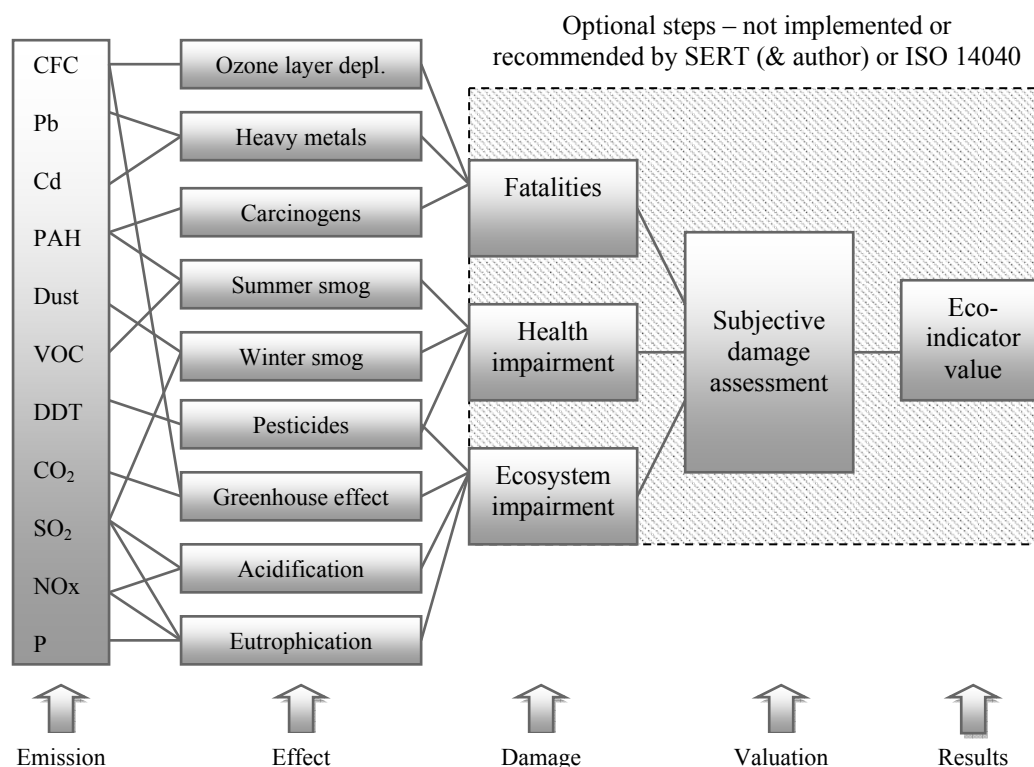


Figure 3-2 The structure of Eco-indicator 95
(Source: Goedkoop, 1995)

Figure 3.2 begins with organising and combining (classifying) the life-cycle inventory results into impact categories. For example, carbon dioxide emissions can be classified into global warming potential and phosphates can be classified as eutrophication. Characterization is then applied by using conversion factors (or equivalency factors) to convert and combine the LCI results into representative indicators of impacts to human and ecological health, enabling the comparison of LCI results within each impact category (EPA, 2006). Taking CO₂ as an example, all greenhouse gases can be expressed in terms of CO₂-equivalents by multiplying the relevant LCI results by a CO₂ conversion factor and then combining the resulting impact indicator to provide an overall indicator of global warming potential (EPA, 2006). Other pollutants are characterized using the distance-to-target principle. The ‘distance-to-target’ principle is selected for the weighting stage of the EI-95 later on also, and it bases its rationale on the premise that there is a correlation between the seriousness of the effect and the distance between the current level and the target level such as that set by national standards (Goedkoop, 1995).

Normalisation is optionally applied next on the impact categories to obtain a relative perspective of the potential seriousness of the effects in comparison to a reference point, such as the European average people's emission equivalents used in Allen *et al.*, (2008a). The EI-95 can go a few steps further to weigh together the different impact categories into damages and then through to the one Eco-indicator value, as shown in the shaded region of Figure 3.6. Ozone layer depletion, heavy metals, and carcinogens may cause fatalities; summer smog, winter smog, and pesticides may cause health impairment; and pesticides, GHGs, acidification and eutrophication may cause ecosystem damage according to the EI-95.

However, the weighting steps of EI-95 are optional steps only (and not recommended) according to ISO 14040 (1997) and ISO 14044 (2006), as mentioned in Chapter 2.2.3 and Figure 2.4, and have also not been advocated by Allen *et al.* (2008a and 2008c) and Hammond *et al.* (2009), due to the highly subjective nature of the ascribed weighting system, particularly in assigning reduction (weighting) factors for impact categories also according to the 'distance-to-target' principle. For example, the EI-95 indicates that an acceptable *target* level would be 1 fatality per million inhabitants per year, or only 5% ecosystem degradation will still occur over several decades (Goedkoop, 1995). This was a subjective choice that 'could not be scientifically based'. To this end, only the characterised values of the EI-95 were used in Allen *et al.* (2008a and 2009c) and Hammond *et al.*, (2009). These values were combined with their respective damage functions from the Externalities of Energy (ExternE) project, where available. This approach, discussed at length below, formed the cornerstone of the original analysis of combining LCA and CBA in Allen *et al.* (2008a and 2008c) and Hammond *et al.* (2009).

The (ExternE) Project commenced in 1991 as the European part of a collaboration with the US Department of Energy in the 'EC/US Fuel Cycles Study' with the objective of producing a workable methodology for detailed quantification of the external costs of fuel cycles (ExternE, 2005a). The outcome of the first part of this project covered the methodology used, mainly the impact pathway approach, and several fuel cycles such as coal, oil, gas, nuclear, wind and hydro. Further European funding enabled the European study team to expand the project by updating the methodology, assessing global warming damages, studying new technologies such as waste and PV, and obtaining nation-specific results (ExternE, 2005a). The project focused mainly on technologies of the 1990s and did not concern itself with 'future technologies that are as of yet unavailable', nor with older technologies which are gradually being decommissioned' (ExternE, 1999b).

The ExternE Project "adopts the impact pathway approach (IPA) for the assessment of the external impacts and associated costs resulting from the supply and use of energy" (ExternE, 1995). It focuses its analysis on airborne pollutants only, ignoring therefore other potential impacts transportable through other means such as through water.

The IPA proceeds 'sequentially' through the pathway from emissions to dispersion, to exposure (impacts) and finally to economic consequences or costs, as illustrated in Figure 3.3 (ExternE, 1995). The IPA is used in combination with the LCA to get a 'complete assessment of external costs due to electricity production, including

impacts that occur upstream and downstream of the power plant itself”, as presented in Figure 3.3 (ExternE, 2005a).

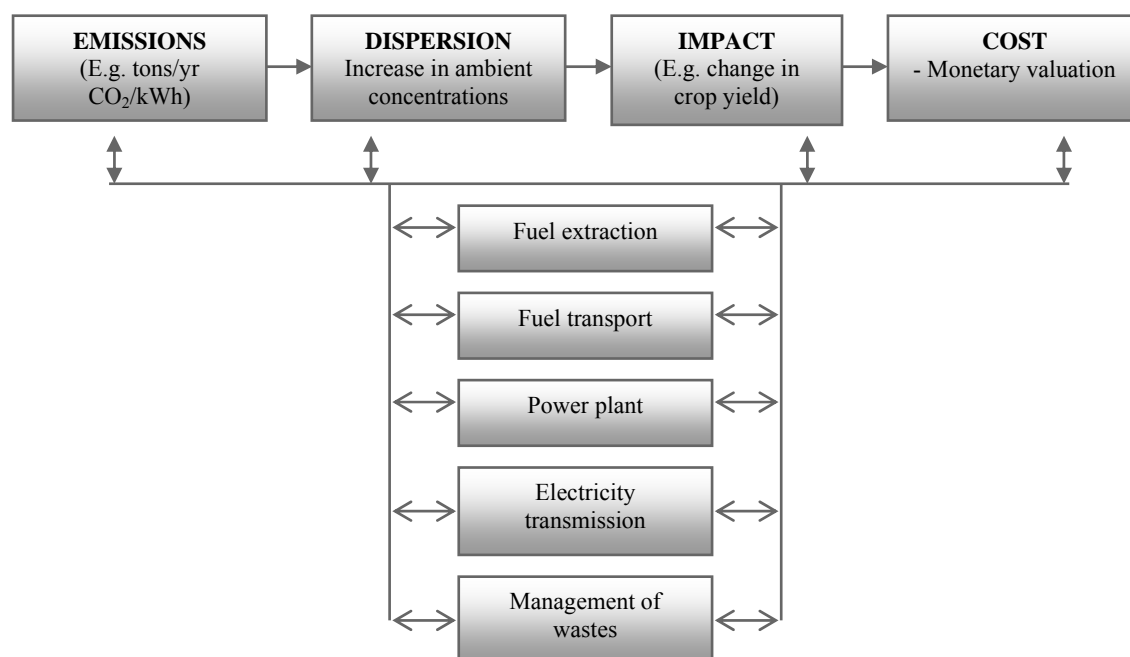


Figure 3-3 Impact Pathways methodology (IPA) applied to pollutant emissions
(Source: IER, 2005)

The IPA illustrated on the horizontal row of Figure 3.3 begins with the ‘emissions (source) stage’, which characterises relevant technologies and the environmental burdens they impose (e.g., tons of CO₂ per GWh emitted by a power plant). ‘Dispersion’ calculates next the increased pollutant concentrations in all affected regions using models of atmospheric dispersion (ExternE, 1994). ‘Impacts’ estimate the physical impacts from the identified ‘dose’, using dose-response functions, and ‘costs’ uses environmental economic valuation techniques (see Appendix 2), where necessary, to monetise the identified impacts (ExternE, 1994). The IPA could be seen as an environmental risk assessment (ERA), discussed shortly, with an additional economic component involved in monetizing the consequences of environmental impacts.

The IPA methodology is linked to LCA in which ‘all components of a given system are analysed from ‘cradle to grave’, covering fuel extraction, transportation and preparation of fuels and other inputs, plant construction, plant or power operation (including emissions) and waste disposal and decommissioning (ExternE, 1995). The boundaries set and used in the analysis have sought to incorporate all aspects of the fuel cycle system deemed to have significant impacts, including such processes and items as the production of steel and cement for construction of plant and extraction and processing of fuel used to transport materials and personnel, despite the inherent complexity of applying this (ExternE, 1994).

The ExternE project also focuses on location or is said to be site-dependent. This is important because there are variations in legal requirements such as emissions

standards or the use of pollution abatement techniques, variation in fuel quality, and differences in the sensitivity of the human and natural surrounding environment between the various European countries (ExternE, 1995). However, results are averaged for Europe (i.e., EU-15 or EU-25)¹³.

In the second stage of the IPA, dispersion of emission needs to be traced. Atmospheric pollution from stacks are transported and diluted by wind and atmospheric turbulence until they are deposited on the ground 'by either turbulent diffusion (dry deposition) or precipitation (wet deposition)' (ExternE, 1999a).

The ExternE project has modelled three groups of atmospheric pollutant transport processes (ExternE, 1999a):

- *Primary pollutants directly emitted from the stack. These include particulate matter and sulphur dioxide (SO₂);*
- *Secondary sulphur and nitrogen species formed from the primary emissions of SO₂ and NO_x. Analysis of these compounds includes modelling the concentration of secondary particulates in the atmosphere and dry and wet (acid rain) deposition processes, and;*
- *Photochemical oxidants, such as ozone, formed in atmospheric chemical reactions.*

Information about the air dispersion modelling techniques and methods used can be found in ExternE (2005a), or other earlier ExternE publications on methodology, such as ExternE (1999a).

These primary and secondary pollutants and photochemical oxidants are liable to cause substantial impacts on human health, building materials, agricultural crops and natural ecosystems. Table 3.1 summarises the main impact categories of the studied air pollutants, along with their respective effects as indicated by the ExternE project.

¹³ EU15 include Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, United Kingdom. EU-25 include the additional European nations of Cyprus, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Malta, Poland, Slovenia.

Impact category	Pollutant/Burden	Effects
Human Health – mortality	PM ₁₀	Reduction in life expectancy due to short and long term exposure
	SO ₂ , O ₃	Reduction in life expectancy due to short term exposure
	Benzene, BaP, 1,3-butad., Diesel part.	Reduction of life expectancy due to long term exposure
	Noise	Reduction in life expectancy due to long term exposure
	Accident risk	Fatality risk from traffic and workplace accidents
Human Health – morbidity	PM ₁₀ , O ₃ , SO ₂	Respiratory hospital admissions
	PM ₁₀ , O ₃	Restricted activity days
	PM ₁₀ , CO	Congestive heart failure
	Benzene, BaP, 1,3-butad., Diesel part.	Cancer risk (non-fatal)
	PM ₁₀	Cerebrovascular hospital admissions, cases of chronic bronchitis, cases of chronic cough in children, cough in asthmatics, lower respiratory symptoms
	O ₃	Asthma attack, symptom days
	Noise	Myocardial infarction, angina pectoris, hypertension, sleep disturbance
	Accident risk	Risk of injuries from traffic and workplace accidents
Building Material	SO ₂ , Acid deposition	Ageing of galvanised steel, limestone, mortar, sandstone, paint, rendering, and zinc for utilitarian buildings
	Combustion particles	Soiling of buildings
Crops	SO ₂	Yield change for wheat, barley, rye, oats, potato, sugar beet
	O ₃	Yield change for wheat, barley, rye, oats, potato, rice, tobacco, sunflower seed
	Acid deposition	Increased need for liming
	N, S	Fertilising effects
Amenity losses	Noise	Amenity losses due to noise exposure
Ecosystems	Acid deposition, nitrogen deposition	Acidity and eutrophication (avoidance costs for reducing areas where critical loads are exceeded)

Table 3.1 Potential effects of pollutants on impact categories
(Source: ExternE, 1999a)

By far the largest share of total costs from energy generation and supply are health-related (mortality and morbidity). However, other impacts like those on buildings, crops and ecosystems are substantial. Impacts on building materials include ‘loss of mechanical strength, leakage and failure of protective coatings due to degradation of materials’ (ExternE, 2005a). With respect to crops, the main impacts on crops are from SO₂ and low-level ozone (formed from the reaction of nitrogen oxides with volatile organic compounds), released mainly from coal-fired plants. Crop yield will increase between 0 to 6 parts per billion (ppb) of SO₂ and decrease thereafter, while a

linear relation between yield loss and the accumulated ozone concentration above a threshold of 40 ppb is assumed (ExternE, 2005a).

Similarly, impacts on terrestrial ecosystems from pollutants released from conventional energy sources such as coal, oil and natural gas are assessed by the ExternE project. Table 3.2 summarizes the potential impacts of different atmospheric pollutants in terms of potential effects on terrestrial ecosystems (including crops).

Pollutant	Forests	Natural flora	Natural fauna	Crops
SO ₂	XX	XX	X	XX
NO _x	X	X	X	X
NH ₃	X	X	X	X
O ₃	XXX	XXX	X	XXX
Total acid	XXX	XXX	X	X
Total nitrogen	XXX	XXX	X	X

X: Indirectly important as a result of interactions with other ecosystem components

XX: Identified as having significant impacts in some areas.

XXX: Highly important and believed to have direct and significant effects over potentially large areas of Europe.

Table 3.2 Relative importance of different atmospheric
(Source: ExternE, 1999a)

The underlying principle used by the ExternE project to quantify environmental externalities is ‘to obtain the willingness to pay (WTP) of the affected individual to avoid a negative impact, or the willingness to accept (WTA) payment as compensation if a negative impact takes place’ (ExternE, 1999a). Three techniques are used to elicit WTP or WTA; either directly via a questionnaire through the contingent valuation method, or through observing market related effects (e.g., property value changes) by using the hedonic price method, or through what is known as the travel cost method where individuals reveal their WTP through expenditures paid to and from a certain amenity (these techniques are summarized in Appendix 2).

The average damage factors per tonne pollutant are indicated in Table 3.3. These damage factors are from the ExternE project and ‘refer to the most important airborne pollutants, taking into account the latest advancements of external costs methodology..., and represent an average location of the emission sources in EU15’ (ExternE, 2005b). A 3% annual discount rate has been used to obtain the values in Table 3.3.

Pollutant	Damage factors (€ ₂₀₀₀ /ton)	Pollutant	Damage factors (€ ₂₀₀₀ /ton)
SO ₂	2,939	Lead	1,600,000
NO _x	2,908	Nickel	3800
PM ₁₀	11,723	Formaldehyde	120
PM _{2.5}	19,539	NMVOC	1124
Arsenic	80,000	Nitrates, primary	5862
Cadmium	39,000	Sulfates, primary	11723
Chromium	31,500	Radioactive emissions	50,000 (€ ₂₀₀₀ /DALY) ¹⁴
Chromium VI	240,000		

Table 3.3 Base damage factors per ton of pollutant emitted in EU15
(Source: ExternE, 2005b)

The UK economy's gross domestic product (GDP) per capita is near-equivalent to that of the EU15, therefore transferring the damage values from Euros (2000) to British Pounds (2009) simply requires using year 2000 exchange rates between the two currencies, and thereafter using the inflation rate for the UK between 2000-2009 to update the damage values to present terms. This procedure, and the results obtained, are expressed in UK Sterling (2009) in Table 3.4, taking into account an average exchange rate of €1.64 to £1 in 2000, and an average annual consumer price index over 9 years (i.e., from 2000 to 2009) of 1.7%.

Pollutant	Damage factors (€ ₂₀₀₀ /ton)	Damage factors (£ ₂₀₀₀ /ton)	Damage factors (£ ₂₀₀₉ /ton)
Ammonia	-	-	-
SO ₂	2,939	1,792	2,085
NO _x	2,908	1,773	2,063
PM ₁₀	11,723	7,148	8,319
PM _{2.5}	19,539	11,914	13,865
Arsenic	80,000	48,780	56,771
Cadmium	39,000	23,780	27,675
Chromium	31,500	19,207	22,353
Chromium VI	240,000	146,341	170,315
Lead	1,600,000	975,610	1,135,442
Nickel	3,800	2,317	2,696
Formaldehyde	120	73	85
Mercury	-	-	-
NMVOC	1,124	685	797
Nitrates, primary	5,862	3,574	4,160
Sulfates, primary	11,723	7,148	8,319
Radioactive emissions	50,000 (€2000/DALY)	30,488 (£2000/DALY)	35,483 (£2009/DALY)

Table 3.4 Base damage factors of pollutants (EU15) based on the ExternE project¹⁵

Allen *et al.* (2008a), and specifically the current author's work, made use of only a few pollutant damage factors from Table 3.4, namely SO₂, lead, and PM_{2.5}, which

¹⁴ DALY stands for Disability-Adjusted Life Years.

¹⁵ As before, the values in Table 3.10 were calculated by ExternE using a discount rate of 3%.

coincide with the parameters characterized in the EI95, specifically ‘acidification’, ‘heavy metals’ and ‘winter smog’ categories, respectively. The EI95 greenhouse effect category, which uses CO₂-equivalents, was also quantified by Allen *et al.* (2008a) and monetized through the social cost of carbon, discussed shortly. However, two main inaccuracies follow in the application of the EI95-ExternE combination, which the current author had not recognized in Allen *et al.* (2008a) and Hammond *et al.* (2009).

The first inaccuracy is related to the use of the characterized values as presented in the EI95 and combining these with the damage functions of single pollutants as estimated by the ExternE project. For example, the ‘heavy metals’ category is characterized according to lead-equivalence in the EI95, based on the Air Quality Guidelines and the Quality Guidelines for Drinking Water of the World Health Organisation (WHO) (Goedcoop, 1995). The maximum allowable concentration according to these guidelines for cadmium, for example, is 0.02 ug/m³, and a 1 ug/m³ limit is set for lead. Therefore the weighting factor in the EI95 is assumed to be 50 kg for cadmium for every 1kg of lead. Looking at Table 3.4, lead is 41 times more damaging cost-wise than cadmium, therefore a slight discrepancy exists equal to the difference between 41 and 50. Furthermore, the EI95 combines also waterborne pollutants (hence the indication of the Drinking Water Guidelines of the WHO above), while the ExternE is solely focused on airborne pollutants. Using therefore the characterization factors of the EI95, with the same damage function for the corresponding particular pollutant from the ExternE project, resulted in an overestimation of the amount of lead (and other characterized values except CO₂-equivalents) in Allen *et al.* (2008a) and Hammond *et al.* (2009), subsequently overestimating the damage cost benefits from these categories.

Secondly, some of the characterization values used by the EI95, such as that of heavy metals, are based also on the ‘distance-to-target’ approach, as mentioned above, and not on actual damage cost values. Although there is significant correlation between the two, using them interchangeably would lead to an inaccuracy given the complete difference in objectives and purposes of these two approaches (distance-to-target and monetization).

There is another impediment from using LCA outputs in CBA. The ExternE project was a LCA project which implemented an environmental risk assessment (ERA) on the more important impacts of several selected fuel cycles in Europe. ERA consists of ‘evaluating the probability that adverse effects on the environment or human health occur or may occur as a consequence of exposure to physical, chemical or biological agents’ (Sonnemann *et al.*, 2004). This necessitates a firm knowledge of the physical-chemical properties of pollutants, biodegradability, potential of bioaccumulation or potential effects of the chemical substances, coupled with a detailed evaluation of emission sources, fate, transport and distribution models in different media (Sonnemann *et al.*, 2004). Specifically, ERA entails a sequence of actions as outlined below (Sonnemann *et al.*, 2004);

- *Hazard identification: identification of the adverse effect that a substance has an inherent capacity to cause;*
- *Exposure assessment: estimation of the concentrations/doses to which human populations or environmental compartments are (or may be) exposed to;*

- *Dose-response assessment: estimation of the relationship between dose, or level of exposure to a substance, and the incidence and severity of an effect;*
- *Risk characterization: estimation of the incidence and severity of the adverse effects likely to occur in a human population or environmental compartment due to actual or predicted exposure to a substance, i.e., the quantification of that likelihood.*

These steps have been implemented by the ExternE project on the important airborne pollutants of fuel cycles. Yet the concern turns to how one can use inventory or characterized inventory estimates from LCA, not linked originally to any site-specific ERA study such as the ExternE project, with damage functions that were estimated through a site-specific ERA (although the ExternE ends up generalising the results of damage functions of airborne pollutants to all Europe). The answer to this raises complex questions that are currently being addressed in the literature. On the one hand, LCA and ERA are said to differ thoroughly in both purpose and perspective, while on the other they could be seen as complementary tools with a spectrum of views in-between (Flemström *et al.*, 2004).

Table 3.5 compares ERA and LCA based on several criteria such as spatial and temporal scale determinants, objectives, principles and dimensions.

Criteria	ERA	LCA
Object	Industrial process or activity	Functional unit, i.e., product or service, with its life-cycle
Spatial scale	Site-specific	Global/site generic
Temporal scale	Dependent on activity	Product life
Objective	Environmental optimization by risk minimization	Environmental optimization by reduction of potential emissions and resource use
Principle	Comparison of intensity of disturbance with sensitivity of environment	Environmental impact potential of substances
Input data	Specific emission data and environmental properties	Mostly (but not always) based on general input and output of industrial processes
Dimension	Concentration and dose	Quantity of emissions
Reference	Exposure potential to threshold	Characterization factor
Result	Probability of hazard	Environmental effect score

Table 3.5 Comparison of ERA and LCA
(Source: Sonnemann *et al.*, 2004)

Looking at Table 3.5, ERA could be said to be an ‘absolute assessment’, in that it requires detailed information on, for example, exposure conditions of specific industrial processes or activities being looking into, while LCA is a ‘relative assessment’ due to the use of a functional unit, for example, the environmental impacts associated with 1 kWh of electricity produced from various generating systems (Sonnemann *et al.*, 2004). In other words, ERA focuses on the total tonnage of one chemical substance, whereas LCA focuses on the product and the system’s functional unit (Flemström *et al.*, 2004). However, LCAs could be applied specifically to certain products.

Table 3.5 also indicates that ERA is site-specific while LCA is site generic. Emissions generated by a product's life cycle occur at many locations, enter multiple media such as air and water, and may cause various impacts subject to the local environment's sensitivities (Reap *et al.*, 2008). ERA accounts for the local surrounding environment where exposures may occur while LCA lacks or assumes global (or regional) homogeneous effects. This means that sufficient information on the background (exposure) characteristics is required for ERA, while generalizations could be made with LCA. For global emissions, such as greenhouse gases, the issue of site-dependency is irrelevant. However and as mentioned earlier, generalizations are made for ERA (i.e., the ExternE damage values) as well, and values are averaged out to include, for example, all Europe.

Site-specificity for LCA is receiving more attention in LCA literature with a move towards defining the surroundings through what is known as 'only above threshold' methods where processes that have the largest share of emissions in the product's life cycle are identified for additional information about actual location (Potting *et al.*, 1999).

Furthermore, LCA regards time in a 'compressed' way, i.e., "processes and their interventions in the past, present and future are added up without correcting for calendar time..., in many cases applying a steady-state situation" (Hofstetter, 1998). In ERA, a specific activity is followed, and the time frame may differ depending on the project or substance at hand. Therefore LCA is currently constrained by the absence of time and space specifications that can lead to the prediction of actual impacts, and instead relies on 'potential effects' (as in the EI-95). It is based on the 'less is better' premise where a comparative analysis of the differences in emissions between product alternatives would lead to the selection of the alternative which achieves a better (lower) emissions rating of individual or aggregated substances deemed important (Potting *et al.*, 1999).

Flemström *et al.* (2004) have indicated that there could be five types of relationship configurations between LCA and ERA, as shown in Figure 3.2.

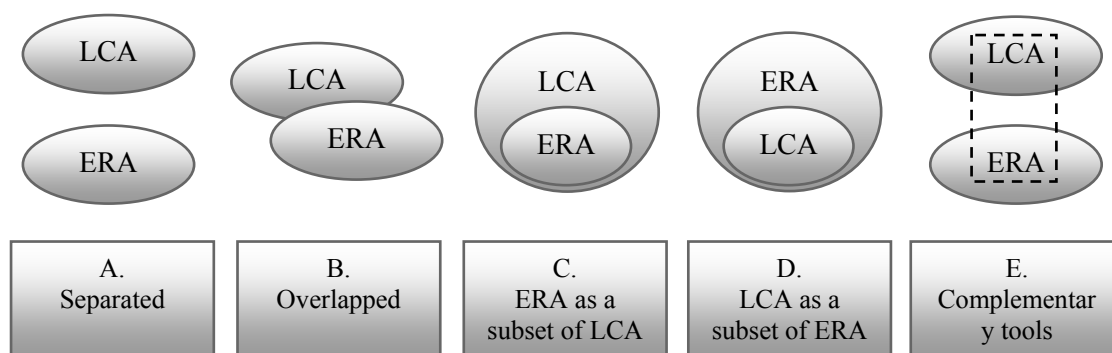


Figure 3-4 Possible relationship configurations between LCA and ERA
(Source: Flemström *et al.*, 2004)

On the one hand, diagram A and B in Figure 3.4 indicate that LCA and ERA are regarded as (A) separated, or (B) slightly overlapping, for example, through the

evaluation of the same impacts such as carbon emissions (Benetto *et al.*, 2007). Alternatively, (C) ERA can often be a subset of LCA, i.e., providing necessary ecotoxicity data for LCIA calculations (Flemström *et al.*, 2004). The Eco-Indicator 99, explained in more detail in Section 3.3.3, is an example of an LCIA which uses ERA related data (dose-response relationships) in its damage assessment (although the exposure environment is generalised or assumed homogeneous). LCA as a subset of ERA (D) is seldom used as ERA is limited to chemicals and not products or services. In Diagram E, LCA and ERA are seen as complimentary tools where ‘detailed risk assessments are implemented on every emission identified in the LCA, i.e., in the inventory through the life cycle chain of a product or service’ (Flemström *et al.*, 2004). Such an approach is shown diagrammatically in Figure 3.5 and is the approach adopted by the ExternE project for the externality costs of electricity production and delivery in Europe.

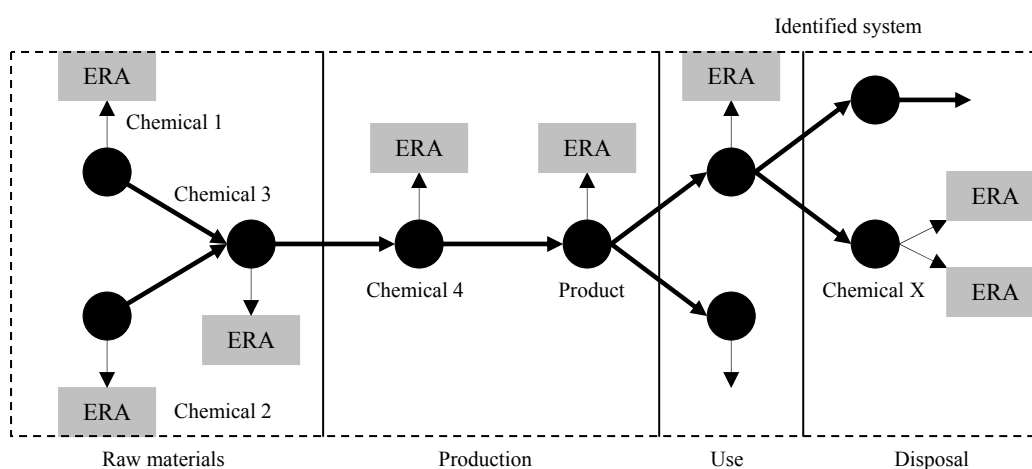


Figure 3-5 Risk assessment performed at every stage of a product's life cycle
(Source: Flemström *et al.*, 2004)

Figure 3.5 shows that ERA can be implemented at every stage in a life-cycle assessment of a product or service. In reality however, this kind of analysis requires extensive time, data and other resources to implement, such as the resources expended by the ExternE project. Moreover, implementing an ERA on every emission identified is harder as more and more processes are identified in contributing to the total environmental impacts. This limitation is shown diagrammatically in Figure 3.6.

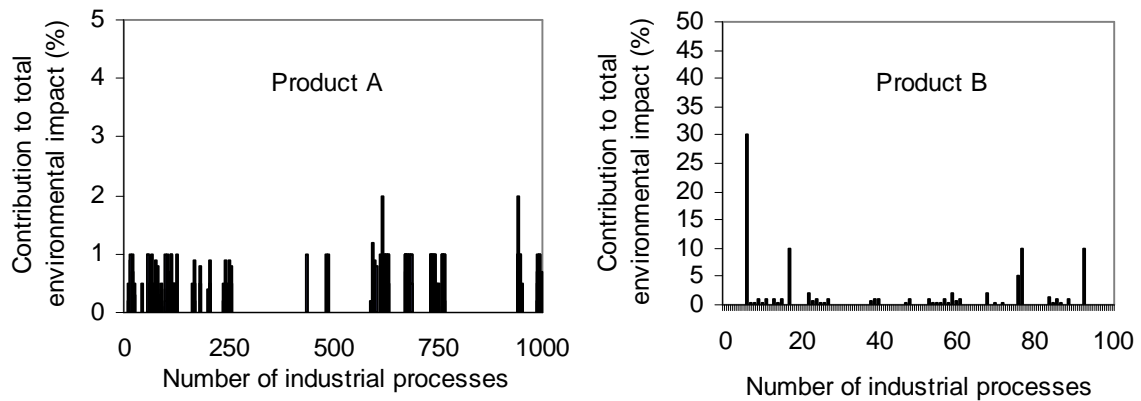


Figure 3-6 Industrial processes contribution to environmental impacts of 2 products, A & B

(Source: Sonnemann *et al.*, 2004)

Figure 3.6 shows two distinct products, for example a computer under product A, and a waste treatment plant under product B (Sonnemann *et al.*, 2004). Sonnemann *et al.* (2004) indicate that if a product (or service) has fewer than 100 industrial processes wherein only a few stand out in contributing to total environmental impacts, as Product B in Figure 3.6, then an ERA is possible on those ‘few’ impacts. This belongs to the ‘only above threshold’ methods discussed earlier. However, if many industrial chains are attributed to the product (or service), as in Product A, implementing an ERA on every process chain becomes a very difficult, and arguably unwarranted, task. The microgenerators assessed in this thesis could be attributed to products belonging to Product A in Figure 3.6.

Given the arguments above, alternative methods for quantifying the environmental implications of the assessed microgenerators are therefore required. The method to link LCA with CBA used in Allen *et al.* (2008a) and Hammond *et al.* (2009) cannot be assumed to be sufficiently accurate given the characterization inconsistencies, although more than half of the environmental impact benefits have come from abated CO₂-equivalent emissions, which do not depend on where the emissions take place (i.e., they are site-generic).

Furthermore, Allen *et al.* (2008) and Hammond *et al.* (2009) based the monetized environmental impact estimations on values from the ExternE project, as specified in Table 3.4. These values have become more or less superseded, although the main ERA (and IPA) methodology as explained above through the ExternE has not. Damage functions presented by the ‘New Energy Externality Development for Sustainability’ (NEEDS) project would be adopted for the CBA of the assessed microgenerators instead. The NEEDS project was completed early 2009 after almost four and a half years of running. The objective of the NEEDS project was to evaluate the full costs and benefits (i.e., direct or private and external) of energy policies and of future energy systems, both at the level of individual countries and for the enlarged EU as a whole. The NEEDS project “refines and develops the externalities methodology already set up in the ExternE project...”¹⁶

¹⁶ See project webpage; <http://www.needs-project.org/>

Given the shortcomings mentioned above, the author has developed four new methods that can link and join, more accurately, the output of LCA into CBA.

3.3 Four alternative approaches to environmental quantification

Alternative (and updated) approaches to Allen *et al.* (2008a) and Hammond *et al.* (2009) for quantifying and monetizing environmental impacts of the three assessed microgenerators (microwind, PV, and SHW) are required. The approaches developed are shown in Table 3.6.

Name	Description
Approach 1	Quantifying and monetizing the costs and/or benefits of greenhouse gas emissions (GHGs) based on the characterized values of CO ₂ -equivalents through the IPCC global warming potentials and the inventory data of the LCA. This approach is ' <i>climate change focused</i> '.
Approach 2	Quantifying and monetizing the costs and/or benefits of major air pollutants, including greenhouse gases (from approach 1), based on the NEEDS project (or continuously on the ExternE project for damage functions not assessed by NEEDS), using the LCA inventory data. This approach focuses only on important ' <i>airborne pollutants</i> '.
Approach 3	Quantifying and monetizing the costs and/or benefits of health effects and ecosystem quality as identified by LCIA Eco-indicator 99 (EI99). This approach combines new environmental economic cost valuations from the NEEDS project tailored specifically to the EI99.
Approach 4	Quantifying and monetizing the costs and/or benefits based on the LCIA Environmental Priority Strategies (EPS) 2000 method. This approach focuses on the ' <i>willingness-to-pay</i> ' (WTP) principle.

Table 3.6 Four alternative approaches to quantifying environmental impacts

The approaches selected in Table 3.6 have been decided upon after much deliberation and careful review of LCA and LCIA methods. Approaches 1 and 2 rely solely on the inventory of the LCA, whereas approaches 3 and 4 rely on LCIA methods.

Approach 1 focuses on GHGs given the encompassing importance of climate change as an emerging environmental situation facing the 21st century, as discussed in Chapter 1. Approach 2 develops, corrects and updates the work done by Allen *et al.*, (2008a) and Hammond *et al.*, (2009), combining the major air pollutants that have damage functions estimated in the NEEDS project (and the ExternE project) with the LCA inventory, and gives justifications for the credibility of doing so. Approach 3 focuses only on health effects and ecosystem quality as identified by the EI99. Finally, approach 4 uses the EPS 2000 to include environmental costs and/or benefits directly into the assessment through the WTP indicators used in EPS2000.

These approaches will be discussed separately below, and a summary of their respective methodological accuracy, completeness, and compatibility within the integrated assessment of the selected microgenerators will be reviewed in Section 3.5.

3.3.1 Approach 1

The first approach of quantifying and monetizing environmental externalities is based on the quantification of the marginal social (damage) cost of carbon only, given the contribution of carbon emissions (and other GHG emission-equivalents) to global warming.

The social cost of carbon (SCC) is the marginal damage of carbon emissions, and is usually estimated ‘as the net present value of the impact over the next 100 years (or longer) of one additional ton of carbon emitted to the atmosphere today, and is expressed as the economic value (in USD or £) per tonne of carbon’ (AEA Technology, 2005). It depends on the amount of greenhouse gas concentration at the time of emission as well as on the amount of greenhouse gas emissions discharged over the atmospheric lifetime of the gas, and therefore the value will vary over time until the concentration of GHGs in the atmosphere stabilises (Clarkson & Deyes, 2002). Moreover, Pearce (2003) has indicated that the monetary value of damage from GHG emissions is likely to grow in the future due to the anticipated increase in incomes translating into higher willingness to pay estimates to avoid warming damage (Pearce, 2003).

The methodologies used in modelling the social cost of carbon vary in terms of their sophistication and assumptions, yet all have the similar linkages from emissions to atmospheric concentration, from concentration to temperature change, and from temperature change to damage, including an intermediate stage from temperature to sea-level rise (Pearce, 2003).

In a ‘highly’ simplified form expressed in Equation 3.1, the total damage, V , from the emission of one extra ton of carbon will be equal to the present value of all future incremental damages, $\partial D/\partial E$, since ‘the carbon resides in the atmosphere for a long period’ (Pearce, 2003).

$$V = \sum_0^T \frac{\partial D_t}{\partial E_t} \cdot (1 + r)^{-t} \quad 3-1$$

In Equation 3-1, ‘ t ’ stands for time and ‘ r ’ stands for the social discount rate. The marginal damage cost of carbon indicates ‘the change in the present value of all future damages from releasing one extra ton of carbon’ (Pearce, 2003). Appendix 3 portrays the simplified mathematical description of the linkages that lead to Equation 3.1 above, based on Pearce (2003).

The literature focusing on calculating the social cost of carbon delivers a wide range of values depending on the calculation technique used (and whether or not the calculation encompasses social, environmental and economic effects, not merely market damages), the discount rate selected, the use of equity weightings, the study time horizon, the inclusion of future socio-economic implications (i.e., assuming a wealthier future), and the inclusion of ‘autonomous’ adaptation¹⁷ among other parameters (AEA Technology, 2005).

¹⁷ ‘Autonomous’ adaptation means adaptation that occurs without explicit policy intervention from the government (Tol, 2005).

Uncertainties are therefore significant in both the ‘scientific’ postulations and the ‘economic valuation’ suppositions. These scientific and economic uncertainties are not exclusive to carbon emissions, yet can be associated with the quantification and monetization of other pollutants assessed through approach 2. Clarkson and Deyes (2002) point to these uncertainties under the two headings presented in Table 3.7.

Scientific Uncertainty	Brief description
Current level of emissions	Uncertainty exists with non-CO ₂ emissions like methane
Future level of emissions	Future socio-economic landscape (e.g. population & economic growth & carbon intensity of production, cost of technology abatement in future...) are uncertain, therefore stabilisation of CO ₂ emission scenarios are uncertain.
Emission level translation to atmospheric concentration of GHGs	Some emissions would be absorbed, in the case of CO ₂ , either by the ocean or by vegetation through sequestration (yet the amount absorbed is subject to uncertainty (deforestation/afforestation would be a factor here). Furthermore, climate change itself will alter the capacity of the oceans and vegetation to absorb CO ₂ .
Climate impact resulting from an increased concentration of GHGs	Not only is there an increase in mean global temperatures, but also secondary impacts like increased levels of precipitation, a rise in the sea level and the increased occurrence of extreme weather events – (greater uncertainty when one attempts to disaggregate these impacts to a regional level). Also uncertainty about runaway greenhouse effects and sulphate aerosols cooling effects from fossil fuel burning. Lastly, once anthropogenic climate change is quantified, it must be superimposed upon the underlying natural variability of the global climate.
Identifying physical impacts associated with climate change	Uncertainty exists when considering vulnerability of our socio-economic landscape, which changes over time as societies invest to adapt to climate change. Therefore identifying and predicting physical impacts is subject to considerable uncertainty.
Economic Uncertainty	Brief description
In valuing costs & benefits of the physical impacts of climate change	Firstly, the same uncertainties herein lie with the uncertainty of the techniques (e.g. WTP/WTB) utilised to value non-market goods – specifically that of risk to human life and ecosystems. Secondly, uncertainty as to how to value physical impacts in different geographical regions; for example, should the climate-related risks to life in different regions be valued at the WTP of the regional population to avoid those risks, or at some global average WTP? (Equity) Lastly, socially contingent damages include those associated with hunger, migration and conflict, and these are largely dependent on the underlying social, economic, and political conditions that exist alongside climate change.
Discount Rate Choice	Very important as damages of one ton of carbon emitted extends beyond 100 years. As an example, damage costing £100 million in 100 years time would have an NPV of £13.8 million at 2% discount, compared with only £0.3 million if a 6% discount is used. The higher the discount the less weight is placed on the costs and benefits occurring in the future (see Chapter 2.4.1.5)

Table 3.7 The scientific and economic ‘valuation’ uncertainties of the SCC
(Source: Clarkson & Deyes, 2002)

Alternatively, uncertainties in the SCC stemming from the science and the economic valuation background could be seen through a risk based approach. Downing and Watkiss (2003) indicate that ‘in looking at the values of the marginal social costs of carbon, each element that derives these values has a different confidence level’. The scientific confidence levels range from ‘quite high’, as for example when projecting temperature and sea level rise within a fairly narrow range, to ‘medium bounded’ risks, where a range could be assigned ‘rough’ probabilities (for example, the probability of changes in summer drought), to ‘quite low’, as for example when considering system changes and surprise (e.g. collapse of the West Antarctic Ice sheet) (Downing *et al.*, 2003). Similarly and on the other hand, estimates of economic damages range in confidence, from ‘high’ (e.g. market goods that are commonly traded), to lower confidence levels, like the valuation of non-market entities (e.g. health and ecosystems), and finally to ‘least confident’ (e.g. socially contingent issues like regional conflict and poverty caused directly or indirectly by climate change) (Downing *et al.*, 2003).

Downing and Watkiss created a risk-based matrix with vertical scientific uncertainty and horizontal valuation uncertainty, shown in Table 3.3 (Downing *et al.*, 2003).


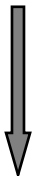
	Uncertainty in Valuation 			
Uncertainty in Predicting Climate Change 		Market	Non Market	Socially Contingent
	Projection (e.g. sea level rise)	Coastal protection Loss of dryland Energy (heating/cooling)	Heat stress Loss of wetland	Regional costs Investment
	Bounded risk (e.g. droughts, floods, storms)	Agriculture Water Variability (drought, flood, storms)	Ecosystem change Biodiversity Loss of life Secondary social effects	Comparative advantage & market structures
	System changes & surprises	Above, plus: Significant loss of land and resources Non-marginal effects	Higher order social effects Regional collapse Irreversible losses	Regional collapse

Table 3.8 The SCC Risk Matrix
(Source: Downing *et al.*, 2003)

Pearce (2003) reviews several studies pertained to the SCC, while AEA Technology (2005) adopts Tol’s (Tol, 2005) reconsideration of literature sources for the social cost of carbon.

Figure 3.7 illustrates the many various values for the marginal social cost of carbon - combined by Tol (2005) from several authors and through various publication years. The values, indicated in US dollars per ton of carbon, indicate a wide range of results as a consequence of using different modelling and mathematical parameters and assumptions.

Tol (2005) found approximately 103 estimates for the marginal SCC from 28 studies reviewed, and combined those estimates into a probability density function. The reviewed studies all use ‘an estimate of the total damage costs, and then slightly perturb the total damages to obtain an estimate of the marginal damage costs’ (Tol, 2005). The review uses four alternative averages, based on the following four criteria (Tol, 2005);

- *A simple average schedule of the studies is used.*
- *All studies receive equal weighting with the exception of three studies.*
- *The author added subjective quality weights (from zero to five, and with 0.1 points per year added to a publication since 1990) consisting of five conditions; is the study peer reviewed? is it based on independent impact assessment? Is it based on a dynamic climate change scenario? Is it based on economic scenarios? Does it measure the marginal damage costs and not the average costs?*
- *Same weights are used but only peer-reviewed ones included.*

The central estimates obtained are wide-ranging, as shown in Figure 3.7 (Tol, 2005). Some damage values seen in Figure 3.7 are even negative, meaning that carbon emission (and therefore climate change) would actually be beneficial in sum, perhaps due to increased agricultural productivity in otherwise cold climates, for example.

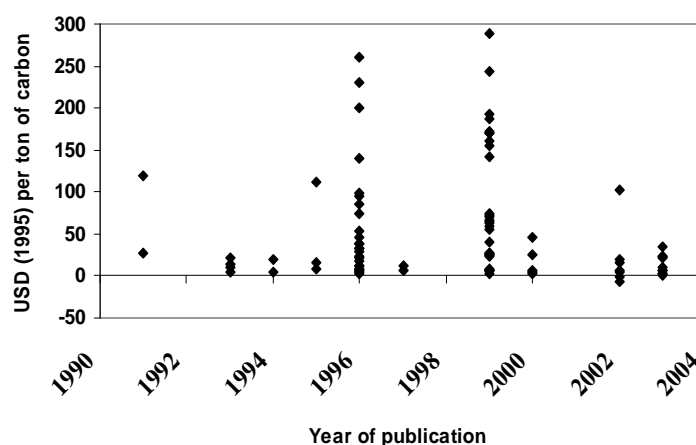


Figure 3-7 Several estimates of the social cost of carbon
(Source: Tol, 2005)

The results by Tol (2005) are given in 1995 US dollars per ton of carbon. However, AEA Technology (2005) transforms these values into 2000 UK Sterling¹⁸ presented in Table 3.9.

¹⁸ The conversion of the estimates cited in the literature review to GBP is based on \$1.42 = £1.00, and we have inflated the 1995 results to USD2000 by using the average U.K. Retail Price Index over the period from 1995 to 2000, an increase of 22.5% (AEA Technology, 2005).

£/tC (2000)	Mode	Mean	5%	10%	Median	90%	95%
Base	1.3	80.2	-8.6	-1.7	12.1	142.3	301.9
Author (<i>Tol</i>) -weights	1.3	111.3	-9.5	-1.7	13.8	189.8	547.8
Peer-reviewed only	4.3	43.1	-7.8	-1.7	12.1	107.8	211.4
No equity weights	1.3	77.6	-6.9	-1.7	8.6	102.7	258.8
Equity weights	-0.4	87.1	-17.3	-1.7	46.6	215.7	340.8
PRTP= 3% only	1.3	13.8	-5.2	-1.7	6.0	30.2	53.5
PRTP= 1% only	4.1	44.0	-12.1	-1.7	28.5	107.8	142.3
PRTP≤ 0% only	6.0	225.2	-20.7	-1.7	33.6	651.3	1388.9

Table 3.9 The probability characteristics of marginal costs of carbon emissions
(Source: AEA Technology, 2005)

The results present a mode of £1/tC, median of £12/tC, a mean of £80/tC, and the 95 percentile amounting to £300/tC (without equity weighting). Using author (i.e., Tol, 2005) preferred weights, the mean becomes £111/tC and the 95 percentile becomes £547/tC. If one excludes the studies that are not peer reviewed, the mean turn out is £43/tC (AEA Technology, 2005).

Therefore, selecting an appropriate measure for the social cost of carbon is highly dependent on many factors, both scientific and economic, and different sources give different ranges or estimates. The ExternE project, for example, has set the social cost of carbon dioxide at €19 per ton (2000 value) (ExternE, 2005b). This is equivalent to £13.5/tC (2009 value) given the exchange rate of £1 = €1.64 in 2000 and taking an average inflation rate of approximately 1.7% for the UK over a 9 year period (2000-2009). The Stern Review, on the other hand, estimates that the current SCC under business as usual could be as high as £68/tC, with a range of £57/tC to £194/tC (Stern 2006)¹⁹. These values are almost in tune with the values estimated by Clarkson and Deyes (2002) for the Department of Food and Rural Affairs (DEFRA). Clarkson and Deyes (2002) adopted and updated values given by Eyre *et al.* (1998) because the latter was viewed as the ‘most sophisticated of the studies published to date’, which considers a ‘wide range of impact categories and geographical regions, uses the most sophisticated modelling techniques, calculates the marginal damages using the marginal cost approach..., and uses a reasonable social rate of time preference of 3%’. For this reason, Clarkson and Deyes (2002) perceive the equity-weighted²⁰ value of approximately £70/tC (2000 prices), raised by £1/tC each subsequent year (thus in 2009, the cost value is £79/tC in 2000 values), as a ‘defensible illustrative value for carbon emissions in 2000’. Clarkson and Deyes (2002) view the value of £70/tC to be most likely consistent with ‘the level of effort needed to meet the UK’s ongoing international commitments on climate change’.

Clarkson and Deyes (2002) do not deny the considerable uncertainties in such an estimate, which they indicate is higher than most values in many studies (at the time). To this end, they advise on performing a sensitivity analysis arbitrarily selected to equal half the size of the central estimate (i.e., £35/tC), and another twice the central

¹⁹ http://www.hmrc.gov.uk/exrate/yearly_rates.htm, <http://www.uktradeinfo.com>

²⁰ Equity-weighted entails that potentially serious impacts in developing countries should not be undervalued.

estimate (i.e., £140/tC), for emission in the year 2000, subject to a £1/tC yearly increase in the central estimate’.

The values of Clarkson and Deyes (2002) were used in Allen *et al.* (2008a) and Hammond *et al.* (2009), however more recent research from the “Cost Assessment of Sustainable Energy Systems” (CASES)²¹ project have lowered slightly the central estimate for the marginal damage costs of CO₂ and significantly lowered the lower range, as shown in Table 3.10.

	Low		Central		Upper	
	€(2000)/ tCO ₂	£(2009)/ tC	€(2000)/ tCO ₂	£(2009)/ tC	€(2000)/ tCO ₂	£(2009)/ tC
2010	5	13	28	71	65	166
2020	6	15	33	85	88	228
2030	8	21	41	106	110	285

Table 3.10 **Estimates for the social cost of carbon in the CASES Project**
(Source: Kuik & Brander, 2007a)

The estimates based on Kuik and Brander (2007) in Table 3.10 capture the uncertainty range given the difference between the low and upper values, and given the fact that they are more updated than the ExternE project and the value range recommended by Clarkson and Deyes (2002), they would be adopted as the social cost of carbon for our analysis²². The quantified carbon-equivalent emissions (or reductions) from the use of microgenerators have been adopted from the characterized values of the IPCC 4th assessment report (IPCC, 2007), using the 100-yr global warming potential.

3.3.2 Approach 2

Approach 2 is Approach 1 above in addition to the inclusion of other important airborne pollutants based on the inventory of the LCA, monetized through damage functions of the NEEDS project, except for PM₁₀ and sulfates, which would be adopted from the ExternE project as presented in Table 3.4.

This approach was illustrated theoretically in Figure 3.5. Significant restrictions exist however when applying this approach to the assessed microgenerators, particularly as the emissions of the manufacturing processes involved in making these systems follow Product A in Figure 3.6, i.e., they are made of multiple small processes each with a few environmental impacts as opposed to a few major ones, and moreover are not related to the actual damage functions estimated by the NEEDS (and ExternE) project. However, some support is given to this approach through a study by Krewitt

²¹ See; <http://www.feem-project.net/cases/> for a description (and objectives) of the CASES project.

²² It is important to note, however, that the UK government has shifted its position with respect to basing its policy recommendations on the use of the SCC, as evident in (DECC 2009b)’s publication, “Carbon Valuation in UK Policy Appraisal: A Revised Approach”. Given the uncertainties involved in the SCC, the DECC has opted to use estimates of the abatement costs, as reflected through the traded price of carbon, that will need to be incurred to meet specific emissions reduction targets (DECC 2009b). These are lower cost (price) values than the range assumed by the SCC, outlined above. For CBA however, only the SCC can be used.

et al. (2001), where it was found that country-specific damage factors for air pollutants derived for specific aggregated sectors in the EU-15 (such as, for example, public power sector, production processes, or water treatment and disposal) do not differ much from the EU-15 average damage factors for those air pollutants. Furthermore, and specifically for the electricity-displacing microgenerators, the environmental benefits from displacing grid electricity (which is accounted for in the ExternE/NEEDS projects) were only reduced by the environmental impacts from manufacturing and installing those systems. The latter form only a small part of the overall environmental impacts. Moreover, the standard deviations (expressed in Table 3.11 below) show that there is a wide range of uncertainties within the damage estimates themselves, which increases the chance that the damage costs from the manufacturing of the microgenerators lies somewhere within the same range identified by the ExternE/NEEDS projects. These issues will be returned to in Chapter 8. Therefore, the LCA inventory for air pollutants from the production processes of the microgenerators could be used as well as the displaced energy carriers (electricity, natural gas, or oil) resulting from the microgenerators being installed and running.

This approach was adopted by the author in Allen *et al.* (2008a) and Hammond *et al.* (2009), although subject to significant uncertainties, omissions of some important air pollutants not quantified by the ExternE project, and the omission of other environmental benefits brought forth through other modes such as water and soil, notwithstanding the inaccuracies of using the EI95 characterization values outlined in Section 3.2.

The NEEDS project has updated the values in Table 3.4, and has determined average damage factors for the EU27²³. These new values are shown in Table 3.11. Almost all damage estimates for the indicated pollutants have been increased except for lead, nickel, and non-methane volatile organic compounds (NMVOC). This difference cannot be attributed to the methodology employed, which was also the impact pathway method used by the ExternE project, but more to do with updated scientific information and economic valuation revisions given the time differences (approximately 10 years) of the two studies.

²³ EU25 + 2 additional nations being Romania and Slovakia.

Pollutant	Mean (μ)Damage factors (€2000/ton)	Mean (μ)Damage factors (£2000/ton)	Mean (μ)Damage factors (£2009/ton)	Log-normal Standard deviation, σ_g , (damage per kg)
Ammonia	12,711	7,751	9,020	-
SO ₂	6,752	4,117	4,792	3.42
NO _x	7,063	4,307	5,012	3.55
PM ₁₀	-	-	-	-
PM _{2.5}	24,570	14,982	17,436	2.78
Arsenic	529,612	322,934	375,840	4
Cadmium	83,726	51,052	59,416	4
Chromium	13,251	8,080	9,404	4
Chromium VI	66,256	40,400	47,019	4
Lead	278,284	169,685	197,484	4
Nickel	2,301	1,403	1,633	4
Formaldehyde	200	122	142	-
Mercury	8,000,000	4,878,049	5,677,206	4
NMVOC	941	574	667	-
Nitrates, primary	5,178	3,157	3,674	-
Sulfates, primary	-	-	-	-

Table 3.11 Base damage factors of pollutants based on the NEEDS project
(Source: NEEDS, 2009a, except column 5: Spadaro & Rabl, 2009)

The mean damage values (μ) from the NEEDS project as shown in Table 3.11 are adopted for the analysis of microgenerators except for particulate matter (PM₁₀, i.e., >10 μ m), and sulfates for which no updated information was available. Reliance of the damage estimates indicated to by the ExternE project in Table 3.4 for these two pollutants are followed.

The uncertainties involved in the estimation of the damage functions for the pollutant indicated in Tables 3.11 are significant. They arise from scientific and economic uncertainty similar in context to those discussed for the case of carbon. An innovative way of dealing with these uncertainties, particularly given the combination (and interface) of uncertainties such as atmospheric dispersion, dose-response relationships, and monetary valuation techniques, is to use lognormal distributions (Spadaro *et al.*, 2009; Spadaro & Rabl, 2008). The justification for using lognormal distributions “lies in the observation that the calculation involves essentially a product of factors, and that the resulting uncertainty of the product is approximately lognormal for most damage costs of pollution... Therefore, it suffices to specify geometric means and geometric standard deviations...” (Spadaro *et al.*, 2008). Column five in Table 3.11 indicates the lognormal standard deviation of the damage costs of the listed pollutants (per kg), an outcome also of the NEEDS project. Where information is missing, a default standard deviation of 3 will be assumed. This is an arbitrary value based to be in line with the standard deviations given in Table 3.11. Therefore, the mean cost for each pollutant damage estimate (μ), as shown in Table 3.11, with geometric standard deviation (σ_g), will have a probability of 68% that the true value is in the interval μ/σ_g and $\mu \cdot \sigma_g$, and a probability of 95% that it is within the range of μ/σ_g^2 and $\mu \cdot \sigma_g^2$ (van der Zwaan & Rabl, 2007).

3.3.3 Approach 3

Approach 3 uses the Eco-indicator 99 (EI-99) LCIA method to establish the health and ecosystem impacts of manufacturing and using the microgenerators.

The EI-99 is a damage-oriented LCIA method which tries to take the ‘potential effects’, such as those shown through the EI-95, a step further into ‘potential actual effects’ based on marginal damages. The EI-99 starts with constructing what it calls the ‘technosphere’ or the inventory table, which includes the description of life cycles and emissions, including the allocation procedures. It then models the changes of damages that are ‘inflicted’ in the environment by the inventory table under what it calls the ‘ecosphere’. Finally, the ‘value-sphere’ models the seriousness of perceived environmental damages along several belief-oriented choices to provide the Eco-indicator value (Goedkoop & Spriensma 2001). The EI-99 is shown in Figure 3.8.

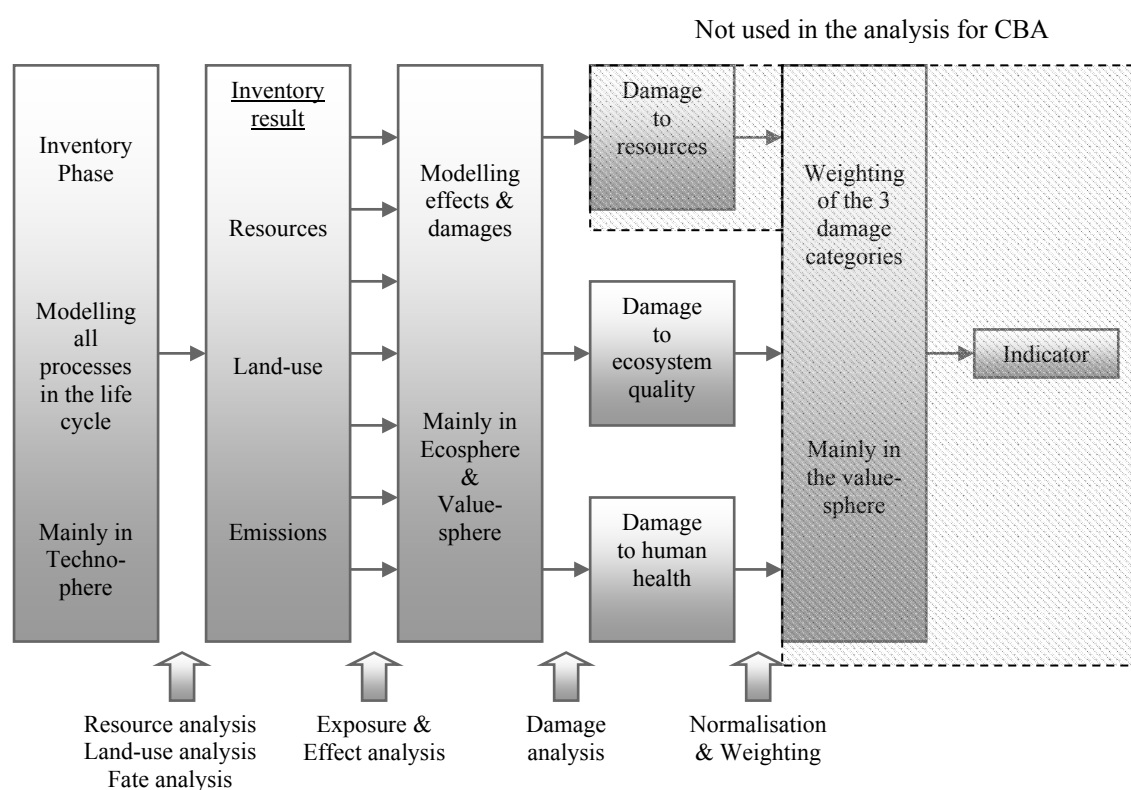


Figure 3-8 The structure of Eco-indicator 99
(Source: Goedkoop *et al.*, 2001)

In EI-99, three damage categories: human health, ecosystem quality, and resources²⁴, are characterised; each arrived at through various methods, including ERA data, as discussed briefly below (Goedkoop *et al.*, 2001);

²⁴ The category ‘resources’ is not used in the analysis for the CBA here, given that costs of microgenerators reflect the value of resources.

- *Human health;*
 - a. *Fate analysis linking an emission to a temporary change in concentration;*
 - b. *Exposure analysis linking the temporary concentration to a dose;*
 - c. *Effect analysis linking the dose to a number of health effects;*
 - c. *Damage analysis linking health effects to a number of years disabled (YLD) and Years of life lost (YOLL), in other words in Disability-Adjusted Life Years (DALYs)*
- *Ecosystem quality;*
 - a. *Toxic emissions and emissions that change acidity and nutrients go through the procedures of fate analysis, effect analysis and damage analysis (as in the human health category above), with the outcome in terms of 'potentially disappeared fraction of plants';*
 - b. *Land-use and land transformation is modelled on the basis of empirical data on the quantity of ecosystems, as a function of the land-use type and the area size.*
- *Resource extraction;*
 - a. *Resource analysis (similar to fate analysis), linking an extraction of a resource to a decrease of the resource concentration*
 - b. *Damage analysis, linking lower concentration to the increased efforts to extract the resource in the future.*

Damage assessment in EI-99 begins also with normalisation against a pre-defined reference system, such as that used in the EI-95. Weighting in EI-99 is also based on assigning weights to three damage categories (instead of impact categories) through a panel-led approach set up by Goedkoop *et al.*, (2001), and differentiated however between three value perspectives which the panel members are likely to possess, to enable the subjectivity of the analysis to be better managed. These value perspectives are (and would lead to) the following (Goedkoop *et al.*, 2001);

- *Individualistic, leading to only proven cause-effect relationships being included in the EI-99;*
- *Egalitarian, leading to the inclusion of environmental damages due to the precautionary principle and a longer term perspective;*
- *Hierarchical, the recommended default EI-99 value system, leading to the inclusion of environmental damages supported by scientific and politically established bodies (such as the IPCC for example).*

The recommended EI-99 outcome (hierarchal value perspective) adds the three damage categories shown in Figure 3.8 into an Eco-indicator value through a 40%, 40%, and 20% weighting set between human health, ecosystem quality and resource extraction respectively.

The DALY system is a disability weighting scale between 0 (perfectly healthy) and 1 (death) developed through a number of panel sessions prepared by (Murray & Lopez, 1996) for the World Bank and the World Health Organisation. For example, if a type of cancer is fatal ten years prior to the normal life expectancy, we would count 10 lost life years for each case, meaning each case has a value of 10 DALYs (Goedkoop *et al.*, 2001). DALY is the sum of years of life lost (i.e., health effects leading to death) with years of disability (i.e., morbidity health effects). Years of disability (YLD), in turn, is the relative disability weight (from 0-1) multiplied by the duration of the disability (Sonnemann *et al.*, 2004).

DALY can be monetised through the value of a statistical life that is measured through several ways (Hofstetter, 1998);

- *Willingness to pay or willingness to accept methods based on contingent valuations methods (as described in Appendix 2);*
- *Market approach through actual voluntary expenditures on items that reduce the risk of death, for example, an air bag option for vehicles;*
- *Wage-risks or the increased compensation individuals demand to work in occupations where the risk of death at work is higher than what is deemed normal (providing an estimate of WTA).*

The ExternE project indicates that the value of a DALY is in the range of €27,240 - €225,000 (2000 values) with a median estimate of €74,627 undiscounted (ExternE, 2005a). The discounted (at 3%) median value is equal to approximately €50,000, as shown in Table 3.4. In 2009, a DALY in the UK would range approximately between £20,000 and £160,000, with a mean value of £53,000 (undiscounted) using the same assumptions used earlier for Table 3.4. However, the NEEDS project lowered the values for DALY to a mean of €40,000, ranging from €25,000 to €100,000 (NEEDS, 2006b). The more recent values from NEEDS will be adopted for the analysis (i.e., £18,000 – £70,000 with an assumed mean of £30,000).

Potentially Disappeared Fraction (PDF) and Potentially Affected Fraction (PAF) of species are used in the EI-99 to indicate ecosystem quality. The PAF of species measures eco-toxicity. It is used to measure the toxic stress effect on ‘lower’ organisms that live in water and soil, such as fish, crustaceans, algae, worms, nematodes, and micro-organisms and several plant species, and can be interpreted as the fraction of species that is exposed to a concentration equal to or higher than the ‘No Observed Effect Concentration’ (Goedkoop *et al.*, 2001). The PDF on the other hand is used to express the effects on vascular plant populations in an area and can be interpreted as the fraction of species that has a high probability of no occurrence (which would mean the fraction of the species that have disappeared) in a region due to unfavourable conditions (Goedkoop *et al.*, 2001). This measures the impacts of eutrophication, acidification, and land-use change. 1 PAF is assumed to be equal to 10 PDF according to Goedkoop *et al.* (2001).

Restoration costs of ecosystems are used as proxy for economic valuation of PDF for the EI-99 by the NEEDS project, i.e., “what would be the cost to restore a unit of land area with a higher PDF value (lower biodiversity value) to a unit with a lower PDF value (higher biodiversity value)?” (Kuik *et al.*, 2007). Restoration costs have been assumed from German studies, particularly assessing the costs for the restoration of

habitats from various starting ‘biotopes’ to various ‘target’ biotopes’ (NEEDS, 2008a). German restoration costs in 2004, which are based on different starting points and target biotopes, can be transferred to UK estimates through a ‘purchasing power standard’ between the two nations of 0.95 (NEEDS, 2008a). This leads to an annual costs range of €0.031 - €0.41/PDF/m²/year (Kuik *et al.*, 2007) or approximately £0.024-£0.31/PDF/m²/year (mean £0.18 PDF/m²/year) in 2009 values. These values will be used as lower and upper values in the estimates of ecosystem quality changes. Further discussion on the methodology to monetize the PDF can be found in (Kuik *et al.* 2007; NEEDS, 2008a).

3.3.4 Approach 4

Approach 4 is based on the LCIA Environmental Priority Strategy (EPS) 2000. The EPS 2000 method evaluates impacts on the environment via the impact on the following safeguard subjects; ‘human health’, ‘abiotic stock resources’, ‘ecosystem production capacity’, ‘biodiversity’, and ‘cultural and recreational’ end-points (Steen, 1999b). EPS 2000’s weighting procedure is based on the principle of willingness to pay (WTP) to restore impacts on the safeguard subjects, and covers countries belonging to the Organisation for Economic Co-operation and Development (OECD), taking the year 2000 as the reference point.

Table 3.12 shows the EPS 2000 safeguard subject’s impact categories, category indicators and the default weighting factor measured in environmental load units (ELU), where 1 ELU is equal to 1 Euro (in 2000). The uncertainty factors, calculated from both the scientific and the economic valuation uncertainties, are also shown for each impact category.

Safeguard subject	Impact category	Category indicator	Indicator unit	Weighting factor (ELU/indicator)	Uncertainty factor
Human Health	Life expectancy	YOLL	Person-year	8.5×10^4	3
	Severe morbidity	Severe morbidity	Person-year	1.0×10^5	3
	Morbidity	Morbidity	Person-year	1.0×10^4	3
	Severe nuisance	Severe nuisance	Person-year	1.0×10^4	3
	Nuisance	Nuisance	Person-year	1.0×10^3	3
Ecosystem production capacity	Crop growth capacity	Crop	Kg	1.5×10^{-1}	2
	Wood growth capacity	Wood	Kg	4.0×10^{-2}	1.4
	Fish & meat production capacity	Fish & meat	Kg	1.0×10	2
	Soil acidification	Base cation capacity of soils	Mole H ⁺ - equivalents	1.0×10^{-2}	2
	Production capacity for irrigation water	Irrigation water	Kg	3.0×10^{-3}	4
	Production capacity for drinking water	Drinking water	Kg	3.0×10^{-2}	6
Biodiversity	Species extinction	Normalised Extinction of species (NEX)	-	1.10×10^{11}	3

Table 3.12 EPS default method safeguard & related impact categories and weighting factors
(Source: Dones & Villigen, 2007)

For the safeguard ‘abiotic stock resources’, a market scenario is created where all future generations are included and are imagined to bid on the present abiotic stock reserves. This bid is assumed to be the costs for extraction of an alternative sustainable choice. Specifically, when ‘a resource is depleting, the costs for extraction will increase until reaching an almost constant value representing the cost for a sustainable production’ (Dones & Villigen, 2007). With respect to cultural and recreational safeguards, no WTP values have been provided for by the EPS 2000, leaving this category to be dealt with on a case by case basis. However this safeguard subject is emitted from the EPS2000 used here because the implications of ‘abiotic stock resources’ such as natural gas, oil and coal are reflected in the prices which are internalised in the cost-benefit analysis of the microgenerators. Including them would therefore lead to double-counting.

The EPS2000 is the least accurate of all four approaches and it is sometimes cautioned against using in CBA (see, for example, Reap *et al.*, 2008). The caution comes from the fact that the EPS2000 was made to give industry managers a quick, easy-to-understand assessment of their products' environmental performances through indicators that they would recognize. The method is applied here for future purposes as the method is potentially the most in line with and compatible to the requirements and process of CBA. It has also been used in some literature sources such as in Nguyen & Gheewala (2008).

The EPS 2000 relies in some instances on estimates for WTP provided by the ExterneE project, yet in other cases relies on other European and U.S studies for benefit transfer of values (Steen, 1999a). However, a main difference between the WTP based on environmental economics principles, and the WTP in the EPS 2000 system is that the latter does not regard 'economics' as a safeguard subject and does not discount future streams of costs or benefits. For example, the WTP to avoid an illness is aimed solely at avoiding the illness 'itself', and does not account for such consequences as loss of income due to restricted activity days and the expenditures caused by the illness (Steen, 1999a). Therefore, in many categories, a lower estimate for WTP is likely to be the outcome due to the omission of the 'economic' safeguard. However, much higher estimates results from the EPS2000 given that it uses no discounting in its calculations. The absence of discounting enabled the EPS2000, or approach 4, to yield the most significant levels of environmental benefits in the CBA applied in this study, although discounting is applied in the EPS2000 values in future years. However the original value, in ELU (or Euros), is undiscounted, whereas other estimated values, such as the SCC of £71/tC as used in approach 1, is discounted using a 3% discount rate.

Furthermore, the EPS 2000 is developed, as mentioned above, with the target that 'it would take only 5 minutes to use the EPS 2000 LCIA in the first phases of the product development process to assess which product or system has least impact on the environment, without undermining the requirements under the ISO14040 series (Steen, 1999b). Such a 5-minute target is a further sign that the EPS 2000 should be used with caution.

This distinguishing variation in the WTP concept, in addition to the absence of discounting future streams of benefits or costs due to 'fairness' objectives and the actual 5-minute objective of EPS, brings uncertainty to the inclusion of EPS 2000 values directly into CBA, as proved by the relatively few studies which use EPS 2000 in economic analysis, such as in Nguyen *et al.*, (2008), Reich (2005) and Dahlbo *et al.* (2007).

The main reason for using EPS 2000 in the economic analysis of the microgenerators is due more to show that an LCIA approach that reflects damage estimates through the WTP criteria can fit well into a CBA, and therefore merits future research. The uncertainty factors, as shown in Table 3.12 will be used as the minimum and maximum range in the uncertainty analysis. It is to be kept in mind, however, that the EPS 2000 will yield the highest monetized environmental impact results given the absence of discounting.

3.5 Concluding remarks on environmental impact quantification

One of the main objectives and contributions of this thesis, as mentioned in Chapter 1 and Figure 1.1, is to better link the ecological and thermodynamic dimension of sustainable development to the economic one, in order to advance the overall methodological credibility and consequent output (or implication) merits of using an ‘integrated approach’ to assess the benefits of policies, programs, projects or technologies. However, the analysis provided in Chapter 3 above shows that there is a great deal of uncertainty in dealing with the quantification and monetization of environmental impacts, and not one approach adopted satisfies all necessary criteria of accuracy, certainty, completeness, and compatibility as shown in Table 3.13.

	Approach	Methodology Accuracy	Certainty in outputs	Completeness	Compatibility
1	Climate change	XXX	XX	X	XXX
2	Airborne pollutants	XX	XX	XX	XX
3	EI 99	XXX	XX	XX	XXX
4	EPS 2000	X	X	XXX	XXX
X: Low XX: Average (moderate) XXX: High					

Table 3.13 Credibility criteria for the 4 approaches within the integrated framework

Table 3.13 is a subjective author-weighted credibility assessment system on the four approaches adopted in this Chapter to merge the findings of LCA with monetization techniques of environmental economics. ‘Methodology accuracy’ accounts for the robustness of the methodology used, particularly the linking of LCA and valued damage functions estimated through the NEEDS/ExternE projects. ‘Certainty in outputs’ accounts for how certain or confident one could be with the actual monetized values which have resulted from each respective approach. ‘Completeness’ accounts for how many environmental impact attributes have been assessed by each approach, and compatibility accounts for how harmonious the approach adopted is to the overall ‘integrated approach’ objective, particularly in linking LCA with CBA. Simple subjective indicators of ‘low’, ‘average’ (or moderate), and ‘high’ have been selected and weighted as assessed by the author.

Approach 1 could be considered highly ‘accurate’ methodology-wise, in that the social cost of carbon represents damage costs as ascribed to by environmental economic principles. It is also ‘accurate’ because GHGs are not site-specific, and therefore it does not matter where they are emitted, their impacts will be the same regardless. It is less ‘certain’ however with respect to output results due to the uncertainty involved in confidently knowing the real value for the SCC. Approach 1 also scores low on ‘completeness’, due to the fact that only GHGs and climate change are addressed, while other important environmental consequences presented by the LCA are not addressed. The approach is highly ‘compatible’ with CBA and the ‘integrated framework’ because although it only includes climate change implications, these are not site-specific.

Approach 2 scores moderately in all 4 criteria of Table 3.13. The ‘accuracy’ is lower than Approach 1 because values from the mid-point inventory of the LCA are

combined with values from the ERA-averaged values of the NEEDS (and ExternE) projects. The assumption adopted here is that the damage functions for air pollutants, which were assessed particularly for energy supply in Europe, could be used in other instances and processes in Europe with some confidence, as suggested by Krewitt *et al.* (2001). Approach 2 could be considered more ‘complete’ than Approach 1 due to the fact that it contains other air-borne pollutants, in addition to GHGs, which cause impacts to human health, ecosystems, and important physical assets such as cultural buildings. It also could be considered to fit moderately well with the ‘integrated framework’ analysis as could be observed in (Allen *et al.*, 2008a; Hammond *et al.*, 2009), after correcting for the characterization errors as discussed in Section 3.2 by using the inventory LCA for the individual pollutants only.

Approach 3 has high ‘accuracy’ methodology-wise, given that it’s an end-point LCIA method with indicators of human health and ecosystem quality that are confidently valued in the literature, particularly through the NEEDS project. The ‘certainty’ of the outputs are considered moderate only however for two main reasons. The first is that the endpoint impacts in the EI99 are considered ‘potential real effects’ as opposed to ‘potential affects’ only, meaning that to estimate DALY and PDF in the EI99, an average European spatial scale was considered. Although this could be seen as an improvement from midpoint methods that have no spatial scale considerations, the DALY and the PDF results are still to be considered ‘potential’ real effects, and taking an average for all of Europe is still a significant generalisation. However, this generalisation is reciprocated by the ExternE and the NEEDS projects, as damage functions from various air-borne pollutants are also average for all of Europe. The second limitation is due to the use of ‘restoration costs’ in the valuation of ecosystem quality. Using restoration costs has resulted in an underestimation of the costs of ecosystem quality, particularly given the exclusion of other value attributes, such as intrinsic values that could be better captured through WTP approaches. Approach 3 also scores moderately under the criteria of ‘completeness’, given that some important costs are missing, such socio-economic costs from forced migration, which is captured under the social cost of carbon, and impacts on architectural or the build environment, which is accounted for by the acid rain in approach 2. Approach 3 scores high however with respect to ‘compatibility’. A part of the NEEDS project had the EI99 LCIA method in mind when it monetized DALY and PDF changes. It therefore fits well within the ‘integrated framework’.

Approach 4, or the EPS 2000 method, is the least ‘accurate’ and ‘certain’ of all methods adopted here, given that it’s purpose was to select a more environmental sound process from alternatives within a short period of time, and relied on various sources for the quantification of environmental impacts (including benefit transfers to Europe). However, due to the ‘completeness’ of the environmental themes involved, and the ‘compatibility’ it possesses within the ‘integrated framework’, it was decided to run approach 4 and recommend it for future research in order to better integrate LCA with CBA.

It must stressed that the analysis is not meant to compare the different methodologies and approaches in quantifying and monetizing environmental impacts for the assessed microgenerators, or analysing in detail each method’s advantage and disadvantages, accuracies and inaccuracies. Inversely, the use of 4 options in the analysis was determined precisely because monetizing environmental impacts are uncertain, and

would therefore require approaching the task from various viewpoints and understandings.

4 Energy Analysis and Life-Cycle Assessment of the Microgenerators

The three microgenerators; microwind, PV and BIPV, and SHW, are assessed in terms of their energy performance and environmental life-cycle impact implications. The analysis is based mainly on correspondences between the University of Bath's Sustainable Energy Research Team (SERT), including the author, and the respective UK suppliers for each microgenerator. Given that specific systems were selected and assessed by SERT (and the author), in collaboration with the manufacturers of those systems, the analysis are specifically tailored to these selected systems. However, in order to make the analysis more generic to the UK context, literature sources concerned with the economics of the assessed microgenerators have been reviewed and included, where possible.

4.1 Description of technology

4.1.1 Microwind

Microwind turbine systems (like larger wind system types) come in three basic forms; Horizontal-Axis Wind Turbine (HAWT), Vertical-Axis Wind Turbine (VAWT) or Building Augmented Wind Turbine (BAWT) (Allen *et al.*, 2008c). The most common design, which is the assessed microwind system in this thesis, is a HAWT made up of three blades mounted on a horizontal axis rotating into the wind on a tall tower. The blades drive a generator to generate electricity either directly (as in the case of the microwind) or via gearbox (generally for larger machines). Microwind produces "wild" AC (variable voltage and frequency) current which is converted to DC via a system controller. This DC is then converted back to normal AC current by inverters. Microwind systems in the UK come in various sizes, typically 400 watts (W), 600W, 1 kilowatt (kW), 1.5 kW 2.5kW, 6kW, and 15 kW (among other sizes) power rating at 12-12.5 m/s with usual cut-in speeds (i.e., the wind speed necessary to start the turbine working and generating electricity) of 2.3 - 3 m/s. A schematic representation of the grid-tied microwind system is shown in Figure 4.1.

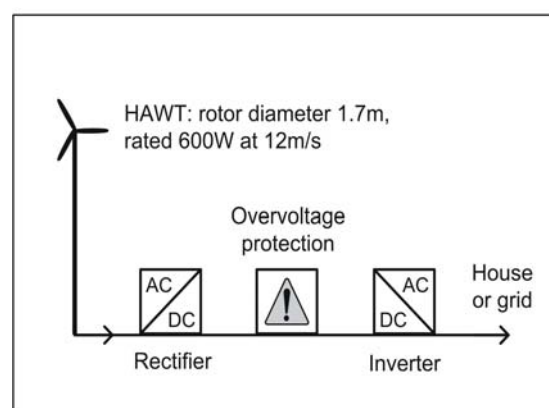


Figure 4-1 Microwind schematic representation
(Source: Allen *et al.*, 2008a)

Figure 4.1 illustrates the grid-tied microwind system which is specifically considered here (in direct cooperation with the system's manufacturer)²⁵, consisting of a rotor

²⁵ Assessment microwind system's manufacturer is Ampier; www.ampier.com.

diameter of 1.7 meters and a power rating of 600W at 12 m/s with a 700W AC inverter. The expected and assumed lifetime of the system is 15 years.

4.1.2 PV and BIPV

PV systems, in simple description, are systems used for the conversion of solar energy directly into electricity through solid state devices (Boyle, 2004). PV cells are the building block of a photovoltaic module, which are simply a number of photovoltaic cells electrically interconnected in either series or parallel and mounted together. A complete set of components for converting sunlight into electricity by the photovoltaic process, including array and balance of system components is known as the PV system.

Solar cells can be grouped as wafer-type (single crystalline or multicrystalline) and thin film. Wafer-type are made from silicon ingot and can currently reach efficiencies between 12 – 15%, while thin film are ‘deposited directly onto a substrate like glass, plastic or steel’ and can currently reach efficiencies between 6 – 11% (van der Zwaan & Rabl, 2004).

A PV grid-tied system is schematically shown in Figure 4.2. Direct current (DC) electricity produced is channelled to the PV array combiner box (or PV array junction box) through cables which then transfers the DC electricity to the grid-tied inverter. The inverter then converts the DC charge into alternating current (AC) that is used either in-house or sold to the grid (Antony *et al.*, 2007).

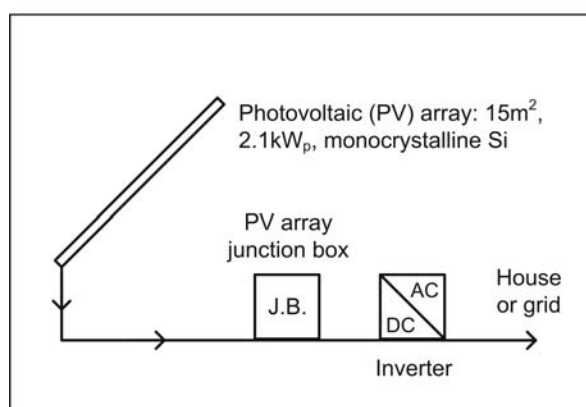


Figure 4-2 **Grid-tied solar photovoltaic array**
(Source: Allen *et al.*, 2008a)

In contrast, in the standalone PV system (known also as an island system), the DC electricity produced by the modules is used to directly charge batteries via a solar charge controller. If the appliances to be used utilise DC electricity, then these appliance are powered directly from the batteries, however if AC electricity is needed, an inverter is connected directly to the batteries (Antony *et al.*, 2007).

The specifically assessed system is a grid-tied 2.1 kWp monocrystalline system with 15 m² of arrays (as shown in Figure 4.2) and a 2.5kW inverter (see Allen *et al.*, 2008a).

The expected and assumed lifetime of the system is 25 years as this coincides with typical PV cell warranties of 20-25 years, although it is claimed by the corresponding manufacturer that the PV system's lifetime can exceed 25 years. On the other hand, the PV inverter will require changing mid-way through the PV system's lifetime.

In parallel, a similar PV system is assessed when constructed on a modern UK domestic detached or semi-detached household building by integrating the modules unto the roof directly, displacing the need for the same quantity of conventional roof tiles - in this case concrete. The system would be referred to thereby as a building integrated PV (BIPV) system, and it has been assessed by Hammond *et al.* (2009a and 2009b), both reproduced in Appendix 8.

4.1.3 SHW

The most common solar hot water (SHW) system is the flat collector panel (alternative are evacuated tube collectors) installed on the roof of a house, 'typically 3 – 5 square metres (m²) in area', linked to an insulated storage tank of 200 litres (could be slightly larger or smaller) and run via a 'pumped circulation system to transfer the heat from the panel to the store' (Boyle, 2004). Sensors are attached to 'detect when the collector is becoming hot so to switch on the circulating pump' (Boyle, 2004). The panel, which is 'sprayed with a black paint to maximise solar absorption', consists of a main absorber such as a 'steel plate bounded to copper tubing through which water circulates', is normally covered with 'a single sheet of glass or plastic, and is insulated from the back to cut heat losses' (Allen *et al.*, 2008a).

Figure 4.3 illustrates schematically the flat plate SHW system which is assessed in this Chapter²⁶.

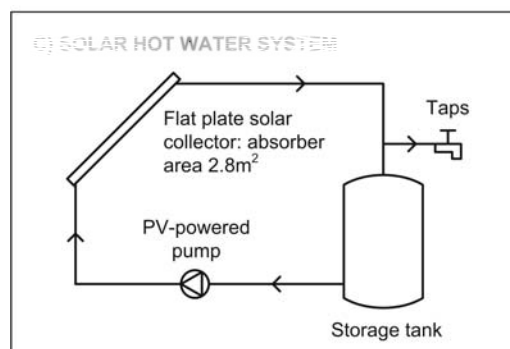


Figure 4-3 Solar Hot Water
(Source: Allen *et al.*, 2008a)

The assessed SHW system, as shown in Figure 4.3, comprises a 2.8 m², freeze tolerant, flat-plate collector typical for installations for 1 - 4 householders (Solar-Twin, 2006). Water is provided to the collector by means of a solar photovoltaic-powered pump. It is assumed that the SHW collector would be connected directly to an existing hot water cylinder that is filled by a vented cold water tank, the latter being fed by the mains supply. An existing central heating system provides auxiliary heating to the hot water tank whenever the SHW system is insufficient to meet

²⁶ The manufacturer of the assessed system is Solar-Twin; www.solartwin.com

demand (Allen *et al.*, 2009). Three options for auxiliary heating systems are considered; a gas-fired central-heating boiler, an oil-fired central-heating boiler, and an electrical immersion heater.

4.2 Energy analysis

The energy performance of the three microgenerators are assessed respectively below, giving a minimum (or low), mean, and maximum (or high) energy output possibilities for each, respectively.

4.2.1 Microwind

The energy (electricity) output of the considered microwind system depends on several factors, most notably the specific geographic location (including terrain type and surroundings) and meteorological conditions (actual wind speed), in combination with the height of the microwind turbine above ground (local positioning of the system) that relates inversely to the degree of turbulence intensity.

The theoretical maximum power that may be extracted from the gross instantaneous power of wind, or what is known as the Betz Law (after a German physicist Albert Betz), is approximately 59% (Allen *et al.*, 2008c). The gross instantaneous power of wind in turn is equal to one-half the density of air multiplied by both the cross-sectional area the wind is passing through and the velocity of wind cubed (in meters per second) (Allen *et al.*, 2008c). Due to ‘aerodynamic and power conversion losses’ however, the actual power curves (relating power output with wind speed) of microwind systems are less than the Betz maximum (Allen *et al.*, 2008c).

Allen *et al.* (2008c) employed the ISO Atmosphere model²⁷ to calculate air densities for the altitudes of the UK weather stations used for wind speed data, adjusting the microwind turbine energy output estimations accordingly (Allen *et al.*, 2008c).

A significant divergence follows in the energy analysis, requiring the categorizing of microwind under two different backgrounds. Differences between the topography and local climatological processes of rural areas versus urban ones, specifically due to the increase in turbulent mixing in the later (Allen *et al.*, 2008c), necessitate the separation of the analysis between microwind systems installed in rural (open) areas or installed in urban ones.

Allen *et al.* (2008c) combined approximately 2.3 million filtered observations based on hourly mean wind speed data recorded between 1990 and 2006 from 18 characterised ‘open’ and 8 ‘urban’ geographic sites in the UK with the microwind system’s published power curve and inverter characteristics (Allen *et al.*, 2008c). The inverter consumes approximately 4W during operation and 0.1W in standby mode when winds are below the required cut-in speed (Allen *et al.*, 2008).

²⁷ The International Standard Atmosphere (ISA) is an atmospheric model of how the pressure, temperature, density, and viscosity of the Earth's atmosphere change over a wide range of altitudes. Details about the ISO Atmospheric model can found in ISO.2533:1975/Add 2, 1997: *standard atmosphere*, International Organisation for Standardization, Geneva, 1997.

The mean annual wind speeds in the open environments were found to range between 2.8 and 7.8 m/s, while those in urban environments ranged between 2.3 and 5.2 m/s (Allen *et al.*, 2008c). Turbulence was estimated to deprive up to 50% of power in the urban terrain compared with 15% for open environments (Allen *et al.*, 2008c).

The annual energy output estimates concluded from the Allen *et al.* 2008b study are illustrated in Figure 4.4. The left-hand vertical axis shows the electricity output (kWh) per annum while the right hand axis indicates the corresponding capacity factor (the actual energy production compared to that achieved if the turbine were to output its rated 600W power continuously).

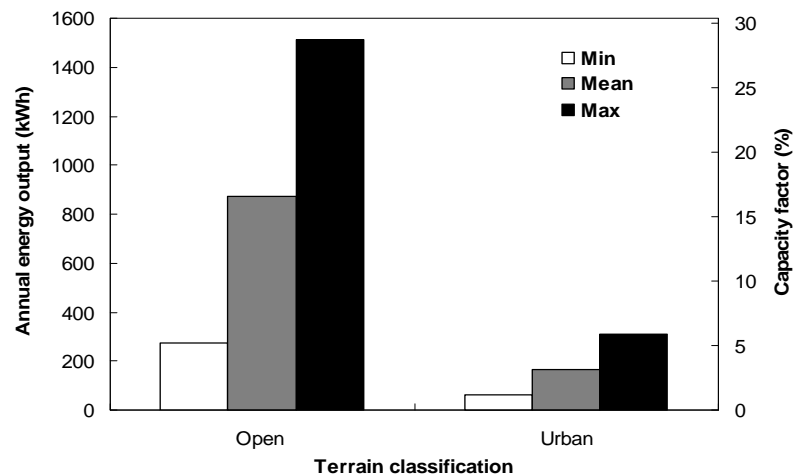


Figure 4-4 Annual energy output estimations for different terrain classifications
(Source: Allen *et al.*, 2008c)

Figure 4.4 shows a dramatic difference between the two terrain classifications (open or urban). The electricity output of the assessed microwind system ranges from 276 – 1516 kWh/year (mean 870 kWh/year) in an open terrain yet only ranges from 62 – 309 kWh/year (mean 164 kWh/year) in an urban one.

Similar results are arrived at by Peacock *et al.* (2008) and Bahaj *et al.* (2007a). Peacock *et al.* (2008) estimated the output of four variously sized microwind systems including a 600W rated system situated in a suburban terrain in Edinburgh, assuming an extrapolated 10 m height and taking two years (2000 and 2001) of recorded data. The capacity factor or the electricity output results of the study are illustrated in Table 4.1 and differentiated between turbine type within a ‘low’ wind site and a ‘high’ wind site.

Turbine rating (kW)	‘Low wind’		‘High wind’	
	Capacity factor (%)	Annual yield (kWh)	Capacity factor (%)	Annual yield (kWh)
0.4	2.3	79	16.2	567
0.6	3.4	180	28.3	1488
1.5	2.1	277	19.3	2541
2.5	2.3	496	22.3	4879

Table 4.1 Predicted annual capacity factor or energy yield for two different wind regimes
(Source: Peacock *et al.*, 2008)

The results of Peacock *et al.* (2008) further support the importance of carefully selected sites for microwind, questioning therefore the rationale behind installing the horizontal axis microwind systems in urban environments. Bahaj *et al.* (2007) lend further evidence as to the implications of terrain on microwind systems by indicating that ‘output from the modelled microwind system is reduced by up to 50% when accounting for wind shear and shadow effects like buildings’, therefore supporting installing these systems on sea front dwellings and within large open spaces (Bahaj *et al.*, 2007a).

Installing a HAWT microwind turbine in an urban environment would not yield sufficient energy (see Figure 4.4), and would therefore undoubtedly be characterized by poor economic performance also. Therefore, and as assumed in Allen *et al.* (2008a), only a system installed in a rural ‘open’ environment would be assessed in this current study. The expected annual energy output range of 276 – 1516 kWh per year (mean 870 kWh/year) as measured by Allen *et al.* (2008c) is therefore adopted for the 600W HAWT microwind system. This range is representative for the UK and is in line with published literature.

4.2.2 PV and BIPV

The expected electricity generation from the 2.1 kWp monocrystalline PV system (and BIPV system) in the UK are obtained mainly by extrapolating results from Suri *et al.* (2007). Estimates of PV energy output values from Suri *et al.* (2007) are validated against the results of two other studies; the DTI (2006a) and Tovey & Turner (2008).

Suri *et al.* (2007) make use of the Photovoltaic Geographical Information System (PVGIS) of the European Commission (EC JRC, 2008), which “combines the long-term expertise from laboratory research, monitoring and testing with geographical knowledge, in order to provide an analysis of national and regional differences of solar electricity generation from photovoltaic systems in the EU25 + 5 member states²⁸” (Suri *et al.*, 2007). Flat-modules PV systems mounted in horizontal, vertical and optimally-tilted positions are considered and compared in order to obtain the generated kWh from each kWp. Inputs to the model constituted of solar radiation from 566 ground meteorological stations (Suri *et al.*, 2007). The resulting grid data spatial resolution is 1km x 1km, representing the period from 1981 to 1990 and containing 12 monthly averages of (1) daily global irradiation on a horizontal surface, (2) the ratio of diffuse to global horizontal irradiation, and (3) clear-sky index which characterizes the cloudiness of the sky (Suri *et al.*, 2007).

Subsequently, Suri *et al.* (2007) calculated the annual total electricity generated (in kWh) from a PV system (E) following Equation 4-1.

$$E = P_k . PR . G \quad 4-1$$

²⁸ EU25 + 5 are the European Union’s current (2007) member states (see footnote 11) with 5 candidate states being Bulgaria, Croatia, the former Yugoslav Republic of Macedonia, Romania and Turkey.

In Equation 4.1, ' P_k ' is the unit peak power (assumed here to be 1 kWp), installed peak power is typically measured in watt-peak (Wp) and it 'characterises the nominal power output of the PV system modules at Standard Test Conditions (STC). STC occurs when the irradiance on the plane of the PV modules is 1000 W/m^2 and the temperature of the modules is 25°C (Suri *et al.*, 2007). 'PR' in Equation 4.1 is the system performance ratio or the ratio between the actual output and the nominal output due to losses from 'angular and spectral variation, and system losses in inverters and cables', quoted to be around 0.75 for a roof-mounted system with modules from mono (or polycrystalline) silicon (Suri *et al.*, 2007). The final component in Equation 4.1, ' G ', is the yearly sum of global irradiation on a horizontal, vertical or inclined plane of the PV module (kWh/m^2). On a horizontal surface, Figure 4.5 illustrates that solar irradiation ranges from about 900 to 1100 kWh/m^2 for Britain (i.e. excluding Scotland) and Ireland.

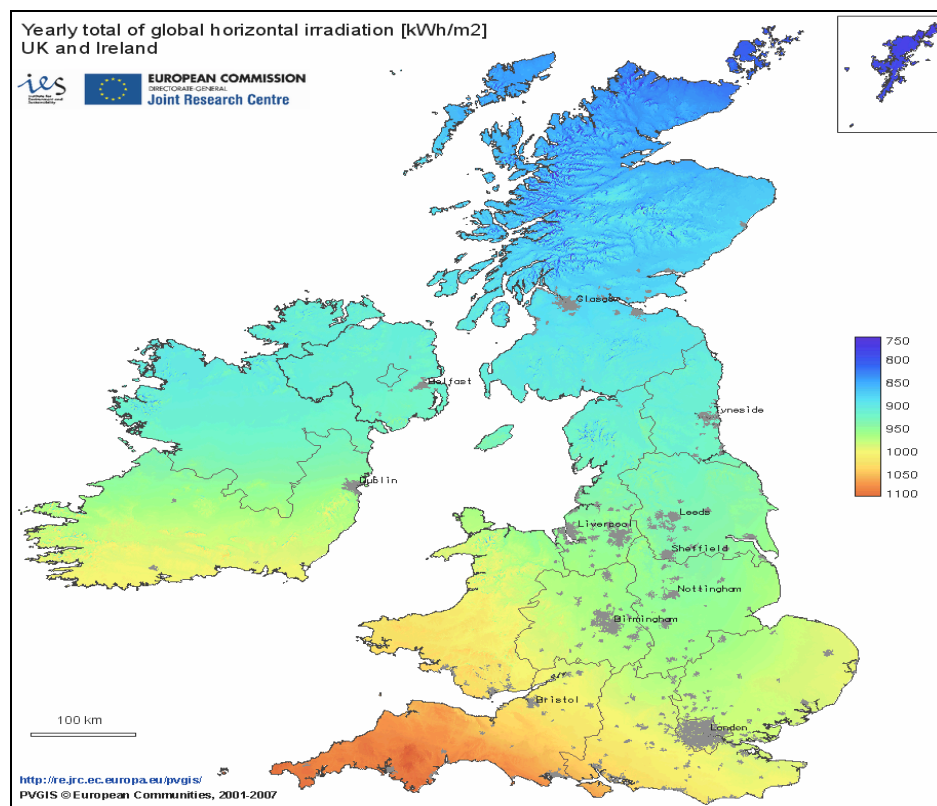


Figure 4-5 Yearly total global horizontal irradiation (kWh/m^2) in the UK & Ireland
(Source: EC JRC, 2008)

The Suri *et al.* (2007) study resulted in the mapping out of solar resource and photovoltaic electricity potential in Europe, including the UK. The outcome showed significant national and regional differences within Europe. 'Less favourable conditions' are found for PV systems for the north-western part of Europe (including the UK), where energy output ranges only between $700 - 800 \text{ kWh/kWp}$ when PV systems are horizontally mounted. 'Optimally' inclined PV systems in those regions (between $36^\circ - 39^\circ$) obtain output increases to between $750 - 900 \text{ kWh/kWp}$.

More specific to the UK context, The DTI (2006) calculated the annual output yield via the PVSYST software²⁹. A 35° south-facing 1kWp system (comprising an array of single crystal silicon modules and a single inverter of capacity 850 Wp had an estimated output of approximately 798 kWh/kWp, based on an average ‘in-plane irradiation level of 2.8 kWh/m² per day’ (DTI, 2006a). This is within the obtained results of Suri *et al.* (2007). Figure 4.6 indicates the annual yield values from several UK sites (17 in total) and 2 years of monitoring (DTI, 2006);

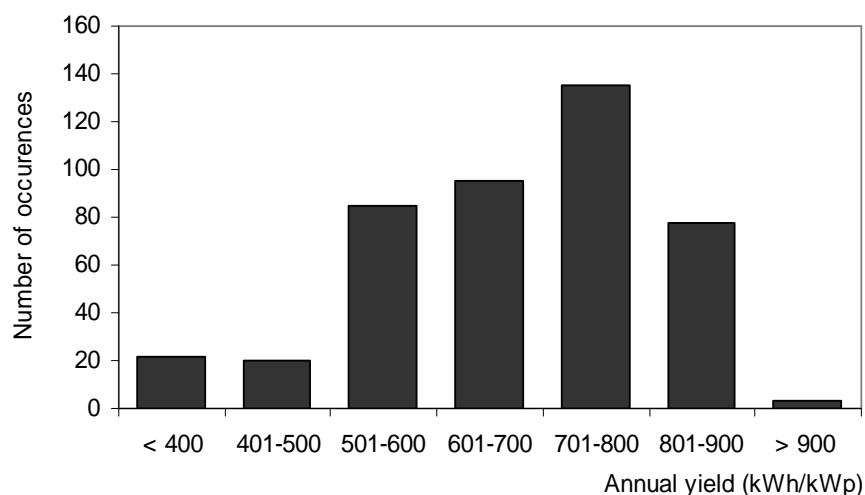


Figure 4-6 Measured annual yield values for PV systems at 17 UK sites
(Source: DTI, 2006)

Tovey and Turner (2008) assessed the performance of a 27.2 kWp monocrystalline PV system integrated into a roof of a university building in Norwich (East England), taking into account inverter efficiencies, the orientation of the PV modules, tilt and extrapolated to other possible regions in the UK. The following parameters were used (Tovey *et al.*, 2008);

- Although the maximum module efficiency of the PV system amounted to 14% (which is also their indicated efficiency at STC), the overall efficiency was approximately 11.1% - which is adjusted also for temperature effects on efficiency;
- The inverter efficiency is estimated to be approximately 91.0%
- Solar radiation datasets used are from the MET office Midas land surface station databases (Meteorological Office, 2009).

Based on a 10-year data of solar radiation in the university building area, the predicted electricity output was estimated to be approximately 820 kWh/kWp. Extrapolated to other regions in the UK, the output of a PV system can range from the worst to the best locations in the UK between 626 kWh - 906 kWh per kWp (Tovey *et al.*, 2008). In addition, Tovey *et al.* (2008) have included an annual degradation rate of PV output by 0.7% over a 25 year estimate of the system.

²⁹ PVSYST 4.3 is a PC software package for ‘the study, sizing, simulation and data analysis of complete PV systems - suitable for grid-connected, stand-alone, pumping and DC-grid (public transport) systems - and offers an extensive meteorological and PV-components database (University of Geneva 2009).

Given the estimate ranges of the three studies reviewed above (and others concerned with PV in the UK, for example, see Bahaj *et al.*, (2007b)), the annual energy (electricity) output range of the assessed 2.1 monocrystalline PV (and BIPV) system is in the range of 1300kWh – 2000kWh, with a mean of 1720 kWh. The methodology presented above for calculating the annual energy range of the PV and the results obtained were also adopted by Allen *et al.* (2008a) and Hammond *et al.* (2009a and 2009b), and could be confidently taken as highly representative of similar PV systems for the UK. No degradation in the rate of PV output is assumed however in the analysis, in line with Allen *et al.*, (2008a) and Hammond *et al.* (2009a and 2009b), just as no consideration is made of PV's lifetime extending beyond 25 years. In the first instance a possible slight overestimation of PV's economic benefits will result, while in the second a slight underestimation will result (particularly given the impact of discounting on distant benefits).

4.2.3 SHW

The solar irradiation available for a SHW system in the Britain is the same as that estimated for PV systems described above; anywhere from 900 – 1100 kWh/m². However for a typical UK roof pitch of 15 – 50°, and for south-east to south-west facing installations, the energy available will be increased to 10-15%, therefore increasing the annual gross solar resource available to a 2.8 m² solar collector to 2700 – 3500 kWh/yr of global irradiation (Allen *et al.*, 2009, reproduced in Appendix 8).

The amount of energy that the assessed SHW system delivers at the point of use, i.e., in the form of hot water at the tap, depends however on several other important parameters in parallel to the influence of global irradiance (Allen *et al.*, 2009);

- The plumbing layout together with whether or not one water storage tank is used with the auxiliary heater or two separate tanks are used for each,
- The in-let temperature of the water,
- The daily run-off of hot water used

Two notable studies are reviewed by (Allen *et al.*, 2009); the DTI's "Side by side testing of 8 solar water heating systems" (DTI, 2001) and the DTI's follow-up study entitled "Further testing of solar water heating systems" (DTI, 2002), henceforth referred to as DTI Study 1 and DTI Study 2, respectively.

In the original DTI Study 1, eight variants of SHW systems installed side by side and exposed to a similar climate were assessed over a 6 months period. They were subjected to a similar water extraction quantity of 150 litres per day from inlet water at temperature of 10°C, and subjected to two different time of extraction schedules being either (1) entirely at 6.00 pm or (2) 'split' by extracting 40% at 7.00 am, 20% at 12.00 pm, and 40% at 5.00 pm (DTI, 2001).

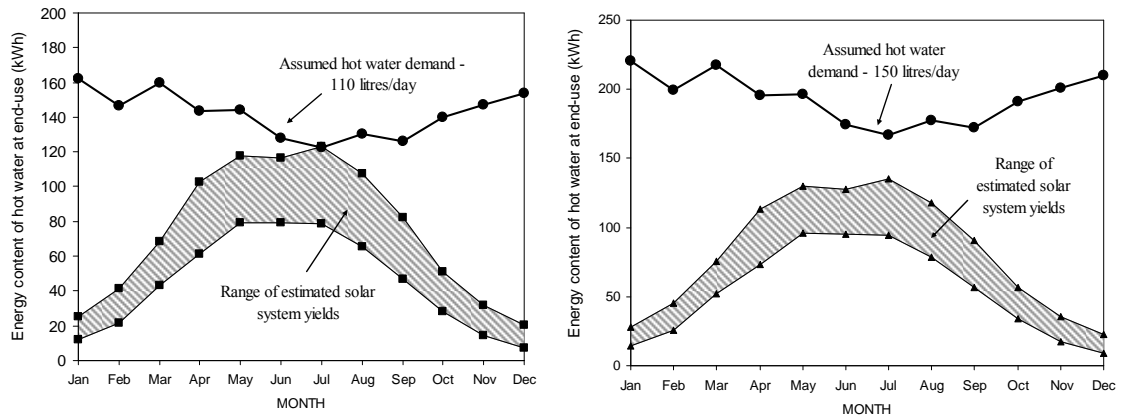
In the analysis here (as Figure 4.3 shows), one storage tank is shared for both the SHW system and the auxiliary heater. The use of one water storage tank as opposed to two separate ones may have two contrasting effects; one reducing losses because of the presence of only one tank as opposed to two, yet the other potentially increasing the losses as auxiliary heating of water creates higher temperatures of water entering the solar collector therefore reducing energy yield (Allen *et al.*, 2009). The energy

losses from the DTI-assumed (and herein adopted) 10 meter long plumbing between the collector and the hot water tank (known as the ‘primary network’) and within the tank storage itself were internalised and therefore reflected in the measurements of the DTI Study 1. However the distribution losses between the hot water tank and the taps are assumed to be 15% of the energy leaving the tank (Allen *et al.*, 2009).

Changes to inlet temperature was considered in the DTI Study 2, considering a higher inlet water temperature equal to the ambient air (on a roof) or the lower temperature of inlet water from the mains supply. The results indicated that a 10% increase and a 5% decrease respectively in annual energy yields occur when compared to results from the DTI Study 1 (Allen *et al.*, 2009). Yet as these inlet temperatures are based on simulations of extreme cases, it is ‘unclear whether they are any more likely than the actual cold water inlet temperatures experienced by the SHW systems during testing in the original field trial’ (Allen *et al.*, 2009). The original inlet temperature results from the DTI Study 1, which average annually 16°C, are therefore justifiable and assumed.

The daily run off comes out as the most influential parameter on the energy output of a SHW system after solar irradiance. The amount of hot water required in a household is a function of the number of occupants in that household according to the function $46 + 26N$ where N is the number of occupants (EST, 2008b). Therefore the 150 litres/day of hot water use assumed in the DTI Study 1 is more representative of a household with 4 persons as opposed to the current UK average of 2.4 persons per households (DTI, 2007). A more representative hot water demand approximating 110 litres a day should therefore also be explored. In the DTI Study 2 this lowering of run-off volume was considered although limited by the selection of only two SHW systems, one of which is a flat-plate system resembling the one assessed here yet with a different plumbing layout (Allen *et al.*, 2009). It was found that reducing the daily run-off to 110 litres/day reduces the energy yield by 17% for our assessed system, and yet is unaffected to any significant extent by the actual run-off time (Allen *et al.*, 2009).

Figure 4.7 summarises the resulting monthly energy content of hot water provided to the end-user by the SHW system, for daily run-off volumes of both 150 litres (Figure 4.7A) and 110 litres (Figure 4.7B). In Figure 4.7A, the annual hot water demand is 2321 kWh, of which the SHW supplies between 647 and 978 kWh – a solar fraction of 28–42%. In Figure 4.7B, the annual hot water demand is reduced by 27% to 1703 kWh, and this is estimated to cause a 9–17% reduction in energy yield. The annual yield is thus reduced to 539 – 889 kWh, while the solar fraction is increased to 32–52%. In this scenario the SHW output is close to meeting demand during the summer months, and satisfies it entirely during July given the highest estimated hot water yield (Allen *et al.*, 2009).

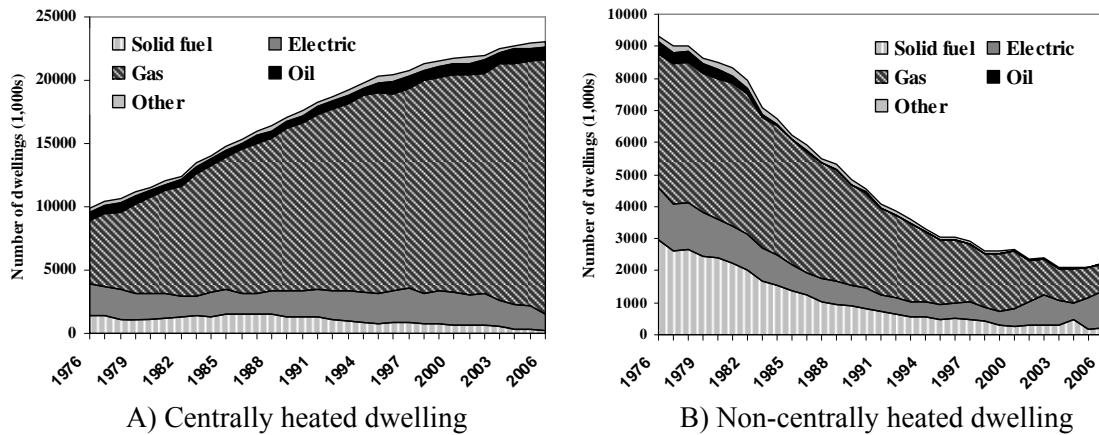


A) Daily run-off volume of 150 litres

B) Daily run-off volume of 110 litres

Figure 4-7 Estimated useful-energy yield of the SHW system
(Source: Allen *et al.*, 2009)

The SHW system is assumed to be installed alongside a gas boiler, an oil boiler, or an electric immersion heater. Therefore, the SHW system would correspondingly (1) displace natural gas use in a gas boiler, (2) or displace oil use in an oil boiler, or (3) displace electricity use in an electrical immersion heater. The justification for selecting these three specific categories are shown in Figure 4.8 A and B (Utley & Shorrocks, 2008).



A) Centrally heated dwelling

B) Non-centrally heated dwelling

Figure 4-8 Heating by type in UK dwellings (1,000s)
(Source: Utley *et al.*, 2008)

Figure 4.8 shows the total numbers of UK dwellings using central and non-central heating. It shows that there are a growing percentage of central heating systems using natural gas, followed by oil and electricity. The ‘conventional’ central-heating boiler is present in about 86% of current UK houses providing space heating and hot water jointly (Williams, 2008). Figure 4.8B shows a decreasing share of non-central heating systems, however with electricity-driven systems (i.e., electric immersion heaters) increasing in the past few years. Furthermore, it was confirmed through communications with the SHW system supplier that their SHW systems are currently installed mainly when oil, natural gas, and electricity are present as auxiliary heating sources, followed by bottled gas, biomass, coal, and wood respectively in order of significance (Allen *et al.*, 2009). Therefore, it would be sufficiently representative in

the UK to select for assessment the above mentioned three main auxiliary heating systems (gas, oil and electricity) next to which a SHW system is installed.

The losses that the auxiliary system experiences “in its primary pipe-work (between the boiler and the storage tank), storage losses, and distribution losses (between the tank and the point of hot water delivery, must be added to the energy yield of the SHW system to give the total energy output required by the auxiliary heater” (Allen *et al.*, 2009). The conversion efficiency of the auxiliary systems can vary depending on the system considered and significant variations can exist within each type itself. However, for the domestic central heating system with regular boiler and separate hot water store as considered here, the boiler must have a SEDBUK (Seasonal Efficiency of Domestic Boilers in the UK) efficiency of at least 86% for gas and 85% for oil (Allen *et al.*, 2009). These values are deemed appropriate for use because although there are boilers with efficiencies of over 90%, there will also be the probability that SHW systems are installed alongside older boilers with lower efficiencies than the SEDBUK specifications. Moreover, natural gas and oil boilers use a small quantity of electricity to power components such as pumps and fans which are included in the analysis.

Table 4.2 shows the minimum and maximum fuel and electricity displacement estimates for each auxiliary heating-system through six alternative cases that are adopted in the subsequent LCA and CBA.

Displaced energy (kWh) due to;	Gas offset		Oil offset		Electricity offset	
	Low	High	Low	High	Low	High
SHW yield	626.7	1137.0	634.0	1150.4	538.9	977.9
Avoided auxiliary PP losses	116.3	216.4	117.7	219.0	0.0	0.0
Avoided auxiliary storage losses	96.9	155.1	98.0	156.9	83.3	133.3
Avoided auxiliary distribution losses	109.8	200.3	111.1	202.6	94.5	172.2
Total fuel offset (kWh)	949.7	1708.8	960.9	1728.9	0.0	0.0
Electricity (kWh)	41.6	54.6	73.6	96.6	716.7	1283.4

Table 4.2 Estimates of annual delivered savings enabled by the SHW system
(Source: Allen *et al.*, 2009)

The smallest fuel displacement occurs in the case of the electrical immersion heater as it is the most energy-efficient water heater within the household. On other hand, the most delivered energy displaced by the SHW system is when the latter is installed alongside an oil-boiler.

4.2.4 Some caveats in energy output estimations

The energy output calculations estimated above have been obtained by combining the manufacturer’s power curves with obtained wind speed and turbulence measurements across the UK for microwind, or from various literature and government field trials combined with the rated power (and capacity factors) of the assessed microgenerators for the PV, BIPV, and SHW systems. For PV and BIPV, this methodology for

obtaining the required energy output could be considered straight-forward and accurate, however for microwind and SHW systems, some caution is advised.

For microwind, field trials have found that a number of published power curves by manufacturers are misleading and consequently the predictions of their energy generation are inaccurate and mostly overstated (EST, 2009a). The manufacturer of the assessed microwind system in this thesis has indicated however that the published power curve of their system is accurate, while many other microwind systems which claim to be 1 kWp in capacity are exaggerated and have lower real capacities when the wind speeds at which the rating took place are factored in. To this end, the energy output of the microwind system assessed in this thesis could be considered accurate.

For SHW systems, the effect of several parameters were assessed above, namely (1) the effect on SHW energy output due to different occupancy rates factored in through two different volumes of hot water uses, (2) time-of-use factored in through two different time-of-use extractions of hot water, (3) Inlet temperature through the consideration of two different inlet temperatures, and (4) plumbing layout of the SHW system, particularly how it connected with the auxiliary boiler. However, a study by Hill *et al.* (2009) has indicated that it is beneficial to measure hot water use directly in a household (as opposed to field trials in laboratory or controlled conditions) in order to assess first-hand how hot water use behaviour in a household, coupled with the usage of the auxiliary heater, effect the performance of a SHW system, consequently impacting its energy output and carbon saving potential. To this end, the calculations of energy output estimated in this thesis for the 2.8 m² SHW system, although tested against several variations of input parameters, may yet still need to be amended in future research to take into account the inter-linkages between the various components effecting the SHW system, including household behaviour.

4.3 LCA output

The characterized and normalized results of microwind are presented in Allen *et al.* (2008a) and Allen *et al.* (2008c) implemented through the EI-95 LCIA method. The characterized and normalized results of PV system are presented in Allen *et al.* (2008a) implemented also using the EI-95. The characterized and normalized results of BIPV system are applied in Hammond *et al.* (2009a) using the EI-95 and Hammond *et al.* (2009b) using the EI-99 LCIA method. The characterized and normalized results of the SHW system are applied in Allen *et al.* (2008a) and Allen *et al.* (2009) using the EI-95 LCIA method.

Results from the LCA presented in this section are only those in accordance with the input demanded for by the 4 approaches outlined in Chapter 3. Approaches 1 and 2 rely only on the life-cycle inventory (LCI), the former for GHGs only and the latter for the most relevant airborne pollutants, in addition to GHGs from approach 1. Approaches 3 and 4 rely on endpoint LCIA methods; the EI99 and the EPS2000 respectively. All results form the data for the CBA implemented in Chapter 5.

4.3.1 The centralised system; simplifying the displaced courier

In the ‘use phase’ of the LCA, the microgenerators are to displace alternative energy couriers, specifically electricity from the UK national grid for all the three assessed microgenerators, and additionally scenarios for displacing natural gas and oil use by the SHW system only.

Therefore, the net environmental benefits of using these systems is based on the environmental benefits from using less energy from the displaced couriers (grid electricity, natural gas, or oil), reduced by respective environmental impacts involved in manufacturing and delivering these systems. The environmental implications of maintenance and disposal of these systems are not included due to the relative immaturity of these technologies (Allen *et al.*, 2008a). However, the required inverter change mid-way through the PV system’s lifetime is included in the LCA, and (Allen *et al.*, 2009) includes the consequences of using 50% recycled aluminium components.

The environmental benefits associated with displaced natural gas use or oil by a SHW system could be considered relatively constant throughout the 25 year life-cycle of the SHW system. On the other hand, the displaced grid electricity mix (by all microgenerators) is subject to substantial change in the near to long-term future, particularly following the current commitment of the UK government to source up to 30% of electricity from renewable sources by 2020, compared to just 5.5% today (DECC, 2009i), and the binding commitment to lower carbon dioxide emissions by 80% by 2050 compared to 1990 levels under the UK Climate Change Bill (OPSI, 2008). Figure 4.9 shows the current electricity grid (2009) and the expected national grid mix by 2020 if the UK Renewable Strategy (DECC, 2009i) recommendations are fulfilled.

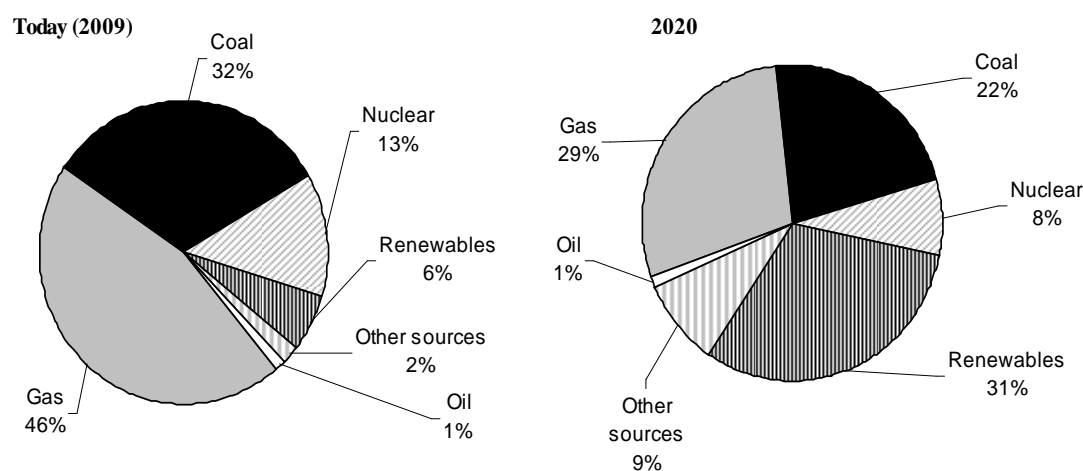


Figure 4-9 UK electricity generation mix; today and expected 2020
(Source: DECC, 2009h)

Implementing a LCA based on assumptions of yearly change of the UK electricity mix is subject to substantial uncertainties (and complexity), particularly given the lack of exact knowledge as to what energy sources (even within similar categories) will be introduced and when, and what energy sources would be retired and when. Therefore, the current (2008-2009) national electricity grid is assumed constant throughout the

analysis, leading to a possible over-estimation of the environmental benefits of the microgenerators displacing grid electricity if the policies and measures endorsed by DECC (2009i) are implemented. However, a second assumption adopted in the LCA for the assessed microgenerators may lead to an underestimation of the environmental benefits from displaced grid electricity. In specific, the reduced consumption of grid electricity induced by the installation of the microgenerators would not happen ‘proportionally’ across all the generating plants in operation, yet would most likely displace output from ‘marginal plants’ that operate in response to demand fluctuation (Kokitsu, 2008). Therefore, the marginal emissions factor would better represent the reduced electricity use as the latter corresponds to marginal plants. In turn, the marginal generating plant being displaced by a microgenerator depends on the total demand on the system at the time that the demand reduction is incurred and on the operation of the system as a whole (Bettle *et al.*, 2006). With respect to carbon emissions at least, the incremental ‘carbon saving’ could be 20-30% higher than those projected by the average emission factor’ (Bettle *et al.*, 2006). This is the case given that the general order in which generating plants are bought online in winter (when peak demand occurs) are nuclear, CCGT, oil and coal respectively (Bettle *et al.*, 2006). The ‘average’ grid mix, or the life-cycle emission factor for electricity generally representing the annual system average value (Bettle *et al.*, 2006), is adopted given the complexities involved in determining the ‘marginal’ plant(s) outputs reduced when the assessed microgenerators are delivering their energy.

The life-cycle inventory for the most important air-born pollutants, including CO_{2e} (used for approach 2), and the impacts expressed through the two LCIA methods (EI-99 and EPS2000 for approaches 3 and 4 respectively) for 1kWh (UK) of national grid electricity, and natural gas and oil delivery and use to the UK household are shown in Appendix 4.

4.3.2 Approach 1; GHG inventory

The GHG emissions that are reduced by using the microgenerators, less the GHG emissions produced in manufacturing and delivering these systems, are presented only through approach 1. The GHG emissions (and reductions) are obtained from the LCA inventory, while the characterization factors of these emissions to obtain CO₂-equivalents are performed as ascribed to by the IPCC, specifically its 4th Assessment Report and taking the most common 100 year-time horizon perspective (IPCC, 2007).

The CO₂-equivalent of the centralised and displaced systems are given in Table 4.3, calculated directly through SimaPro LCA software, which makes use of the IPCC 2007 100-year global warming potential (GWP).

Displaced energy courier	In Kg of CO ₂ -equivalent per kWh
UK grid electricity	0.697
Natural gas (with delivery to point of use)	0.259
Oil (with delivery to point of use)	0.319

Table 4.3 CO₂-equivalents for centralised energy couriers

For every kWh of displaced UK grid electricity, a microgenerator will save approximately 0.7 kg of CO₂-equivalent, while it saves approximately 0.32 kg and 0.26 kg for every kWh displaced of oil and natural gas, respectively. These CO₂-equivalent savings (per kWh) are multiplied by the energy outputs of each microgenerator, as presented in Section 4.2, in order to obtain the annual (and lifetime total) savings. However, these savings in turn have to be reduced by the amount of CO₂-equivalent emissions released during the manufacturing and delivery of each assessed microgenerator, respectively. The total production releases of CO₂-equivalents and annual reduction in CO₂-equivalents are shown in Table 4.4.

Microgenerator	Total CO ₂ -equivalent	Annual CO ₂ -equivalent benefits		
		Output		
	Production	Min	Mean	Max
Microwind	288	158.95	501.05	873.10
PV	4,794	748.70	990.59	1151.85
BIPV	4,061	748.70	990.59	1151.85
SHW (gas)	462	231.48	323.89	416.50
SHW (oil)	462	302.25	423.02	544.12
SHW (elec.)	462	412.94	575.92	738.91

Table 4.4 **Production & net lifetime CO₂-equivalent savings of the assessed microgenerators– Approach 1**

Substantial CO₂-equivalent savings are expected from the operation of the microgenerators over their 25 year lifetime. PV and BIPV, and SHW displacing electricity are the most significant in these terms, equalling approximately 25 tons for PV and BIPV and 15 tons for SHW of CO₂-equivalent in the mean output case, followed by SHW displacing oil and natural gas, and microwind respectively totalling 10.6, 8, and 7.5 tons of CO₂-equivalent. These values will be combined with the respective values for the social cost of carbon (SCC) in Chapter 5.

4.3.3 Approach 2

The environmental impacts (in quantities) of the most important air-born pollutants from manufacturing and delivering the 600W microwind, 2.1 kW_p PV and BIPV, and the 2.8m² SHW systems are assessed and compared against the environmental benefits incurred for the same pollutants by displacing electricity, oil, and natural gas where applicable. As before, the environmental benefits are a function of various energy output possibilities from the microgenerators. For the BIPV system, the additional environmental benefits from displacing UK domestic roof tiles are included as reduced manufacturing and delivery quantities of respective pollutants.

Table 4.5 presents the results of data to be inputted in the CBA of approach 2 (in Chapter 5) for the various microgenerators assessed, in according to their respective expected energy outputs. Annual environmental benefits shown in Table 4.5 are summed in the CBA of Chapter 5 and reduced by the respective production (and delivery) of environmental emissions from the centralised energy couriers, as indicated in annual terms in Table 4.5.

Pollutant	Microwind Production (total kg)	Pollutants saved (kg) per annum as a function of output			PV Production (total kg)	BIPV production (total kg)	Pollutants saved (kg) per annum as a function of output (PV & BIPV output similar)		
		Min	Mean	Max			Min	Mean	Max
Ammonia	0.0135	0.004962	0.015643	0.027258	0.228	0.215	0.023374	0.0309	0.03596
SO ₂	1.391	0.41676	1.3137	2.28916	14.5	14.38	1.963	2.5972	3.02
NOx	0.72	0.3312	1.044	1.8192	10.6	9.82	1.56	2.064	2.4
PM ₁₀	0.0000012	0.14214	0.44805	0.78074	3	2.16	0.6695	0.8858	1.03
PM _{2.5}	0.186	0.032292	0.10179	0.177372	1.32	1.15	0.1521	0.20124	0.234
Arsenic	0.000337	3.61E-05	0.000114	0.000198	0.0053	0.006	0.00017	0.00023	0.000261
Cadmium	0.000101	1.14E-05	3.6E-05	6.28E-05	0.0018	0.002	5.38E-05	7.12E-05	8.28E-05
Chromium	0.00662	2.15E-05	6.78E-05	0.000118	0.003	0.0038	0.000101	0.000134	0.000156
Chromium VI	0.00017	7.12E-07	2.24E-06	3.91E-06	0.000072	0.00009	3.35E-06	4.44E-06	5.16E-06
Lead	0.0012	0.000107	0.000336	0.000586	0.027	0.023	0.000502	0.000664	0.000772
Nickel	0.00076	0.0001	0.000316	0.000551	0.012	0.012	0.000472	0.000625	0.000727
Formaldehyde	0.0029	0.000158	0.000498	0.000868	0.034	0.0251	0.000745	0.000985	0.001146
Mercury	0.000045	5.24E-06	1.65E-05	2.88E-05	0.0003	0.00031	2.47E-05	3.27E-05	0.000038
NMVOC	0.1118	0.015268	0.048128	0.083865	1.92	4.09	0.071916	0.09515	0.11064
Nitrates, primary	0.0000012	4.47E-07	1.41E-06	2.46E-06	0.000017	0.000016	2.11E-06	2.79E-06	3.24E-06
Sulfates, primary	0.00359	0.000442	0.001392	0.002426	0.04	0.544	0.00208	0.002752	0.0032

Pollutant	SHW Production (total kg)	Pollutants saved (kg) per annum as a function of output (SHW displacing gas)			Pollutants saved (kg) per annum as a function of output (SHW displacing oil)			Pollutants saved (kg) per annum as a function of output (SHW displacing electricity)		
		Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
Ammonia	0.01016	0.000342	0.000479	0.000615	0.000772	0.00108	0.00139	0.012892	0.01798	0.023086
SO ₂	1.221885	0.117772	0.164791	0.211908	0.427655	0.598538	0.769867	1.08267	1.51	1.93884
NOx	0.945	0.128266	0.179474	0.230791	0.281823	0.394435	0.50734	0.8604	1.2	1.5408
PM ₁₀	0.3576	0.009279	0.012983	0.016695	0.016558	0.023174	0.029808	0.369255	0.515	0.66126
PM _{2.5}	0.14	0.005033	0.007043	0.009057	0.013954	0.019529	0.02512	0.083889	0.117	0.150228
Arsenic	0.00013013	4.63E-06	6.48E-06	8.34E-06	6.75E-06	9.45E-06	1.22E-05	9.37E-05	0.000131	0.000168
Cadmium	0.00004453	1.52E-06	2.13E-06	2.73E-06	4.56E-06	6.38E-06	8.2E-06	2.97E-05	4.14E-05	5.32E-05

Chromium	0.0001198	2.11E-05	2.95E-05	3.8E-05	2.58E-05	3.61E-05	4.65E-05	5.58E-05	7.79E-05	1E-04
Chromium VI	0.0000028	5.05E-07	7.07E-07	9.09E-07	5.97E-07	8.36E-07	1.07E-06	1.85E-06	2.58E-06	3.31E-06
Lead	0.0004426	1.79E-05	2.51E-05	3.23E-05	2.65E-05	3.71E-05	4.78E-05	0.000277	0.000386	0.000496
Nickel	3.594E-07	1.27E-05	1.78E-05	2.28E-05	5.89E-05	8.24E-05	0.000106	0.00026	0.000363	0.000466
Formaldehyde	0.000688	0.000355	0.000497	0.00064	0.000135	0.000188	0.000242	0.000411	0.000573	0.000735
Mercury	0.0000213	1.96E-06	2.74E-06	3.52E-06	4.5E-06	6.29E-06	8.1E-06	1.36E-05	0.000019	2.44E-05
NMVOC	0.1712	0.069575	0.097352	0.125187	0.147754	0.206794	0.265988	0.039664	0.05532	0.071031
Nitrates, primary	0.000000752	2.75E-08	3.84E-08	4.94E-08	3.3E-08	4.62E-08	5.95E-08	1.16E-06	1.62E-06	2.08E-06
Sulfates, primary	0.0055	9.99E-05	0.00014	0.00018	0.000217	0.000304	0.00039	0.001147	0.0016	0.002054

Table 4.5 Production and annual saved environmental pollutants from operation of the assessed microgenerators – Approach 2 environmental inputs

The specifically quantified air-pollutants in Table 4.5 are monetized via damage functions as estimated by the ExternE and the NEEDS projects. These values form the basis of the environmental impact benefits attributed to the assessed microgenerators according to approach 2, the scale of which is dependent on their respective energy outputs.

Table 4.5 shows that sulphur dioxide (SO₂), nitrogen oxide (NO_x), and large particular matter (PM₁₀) are the largest quantities of air-borne pollutants emitted during the manufacture of the microgenerators and saved from reduced use of natural gas, oil and grid electricity. However, their importance are only verified when their damage estimates, as expressed in Chapter 3.3.2, are factored in. This is done in the implementation of the CBA in chapter 5.

4.3.4 Approach 3

Approach 3 relies on the Eco-indicator 99 (EI-99) for the estimation of environmental benefits and costs of the microgenerators. The two main end-point damage categories to be valued are the DALYs and the PDFs, as justified in Chapter 3.3.3. Appendix 4 shows the impact of 1kWh from the centralised systems (electricity, natural gas, and oil) using the EI-99 LCIA method. Table 4.6 below shows the impacts of producing the microgenerators and the annual expected environmental benefits from reduced centralised energy couriers of electricity, natural gas and oil.

		Microwind production	Microwind Annual benefits				PV production	BIPV production	Annual benefits (PV & BIPV have similar outputs)		
Impact category	Unit	Total	Min	Mean	Max	Total	Total	Min	Mean	Max	
Carcinogens	DALY	0.000074	1.46E-05	4.6023E-05	8.0196E-05	0.000804	0.000764	6.88E-05	9.1E-05	0.000106	
Resp. organics	DALY	0.0000002	2.8704E-08	9.048E-08	1.5766E-07	5.33E-06	6.32E-06	1.35E-07	1.79E-07	2.08E-07	
Resp. inorganics	DALY	0.00036	5.6304E-05	0.00017748	0.00030926	0.003365	0.002869	0.000265	0.000351	0.000408	
Climate change	DALY	0.00007	3.4224E-05	0.00010788	0.00018798	0.001049	0.000887	0.000161	0.000213	0.000248	
Radiation	DALY	0.0000016	1.5649E-06	4.9329E-06	8.5957E-06	2.89E-05	3.01E-05	7.37E-06	9.75E-06	1.13E-05	
Ozone layer	DALY	2.26E-08	8.3076E-09	2.6187E-08	4.5632E-08	5.53E-07	9.06E-07	3.91E-08	5.18E-08	6.02E-08	
Total	DALY	0.0005	0.00010673	0.00033643	0.00058624	0.00525278	0.004557	0.000503	0.000665	0.000773	
Ecotoxicity	PDF*m2yr	55.77	0.928188	2.92581	5.098308	285.5596	255.3144	4.3719	5.78436	6.726	
Acidification/ Eutrophication	PDF*m2yr	5.863	1.752324	5.52363	9.625084	82.20168	74.96904	8.2537	10.92028	12.698	
Land use	PDF*m2yr	5.63	0.573528	1.80786	3.150248	83.82073	68.48477	2.7014	3.57416	4.156	
Total	PDF*m2yr	67.262	3.25404	10.2573	17.87364	451.58201	398.7682	15.327	20.2788	23.58	

Impact category	Unit	SHW production	SHW annual benefits displacing natural gas			SHW annual benefits displacing oil			SHW annual benefits displacing electricity		
		Total	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
Carcinogens	DALY	7.6536E-05	1.17584E-06	1.6453E-06	2.1157E-06	2.1625E-06	3.0266E-06	3.89297E-06	3.7941E-05	5.2917E-05	6.7893E-05
Resp. organics	DALY	3.1558E-07	1.31E-07	1.84E-07	2.3615E-07	2.29E-07	3.21E-07	4.12835E-07	7.42E-08	1.04E-07	1.3285E-07
Resp. inorganics	DALY	0.00032543	2.28518E-05	3.1975E-05	4.1117E-05	6.6573E-05	9.3175E-05	0.00012	0.00014626	0.00020399	0.00026172
Climate change	DALY	0.00010439	5.07957E-05	7.1075E-05	9.1397E-05	6.7939E-05	9.5086E-05	0.000122	8.8887E-05	0.00012397	0.00015905
Radiation	DALY	2.018E-06	1.1271E-07	1.58E-07	2.028E-07	2.2975E-07	3.22E-07	4.13589E-07	4.0681E-06	5.67E-06	7.2794E-06
Ozone layer	DALY	4.9598E-08	3.39E-08	4.74E-08	6.10E-08	4.98E-08	6.97E-08	8.96E-08	2.16E-08	3.01E-08	3.86E-08
Total	DALY	0.000509	7.51011E-05	1.05E-04	0.000135	0.000138	1.92E-04	0.00025	0.000277	3.87E-04	0.000496
Ecotoxicity	PDF*m2yr	12.0153	0.5521	0.7725	0.9934	0.1216	1.70E-01	0.219	2.4113	3.36E+00	4.3148
Acidification/ Eutrophication	PDF*m2yr	6.899	0.861	1.204	1.548	2.1955	3.0728	3.95	4.5524	6.35E+00	8.146
Land use	PDF*m2yr	12.116	0.772	1.0802	1.389	2.6141	3.6586	4.706	1.4898	2.077799	2.666

Total	PDF*m2yr	31.031	2.18	3.0571	3.931	4.9312	6.9	8.88	8.4535	11.8	15.127
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Table 4.6 Eco-Indicator 99 LCIA results for the assessed microgenerators; Approach 3 environmental inputs

Table 4.6 shows that the production of microwind, PV, BIPV and SHW systems are responsible for 0.0005, 0.00525, 0.00456, and 0.00051 DALYs, respectively. The mean (output) total environmental benefits for the systems (equal to the annual results in Table 4.6 multiplied by the respective lifetime of the systems) are 0.005, 0.0166, 0.0026, 0.0048, and 0.0097 DALYs for microwind, PV and BIPV (similar benefits), and SHW displacing natural gas, oil and electricity, respectively. With respect to ecosystem quality, production of the systems cause 67, 84, 68, and 31 PDF/m²/yr for the microwind, PV, BIPV, and SHW systems, respectively. The total PDF/m²/yr benefits of the systems, within their mean output assumptions, equate to 153, 506, 76, 172, and 295 PDF/m²/yr for the same sequence of technologies as above. These values or estimates form the basis of monetizing the environmental impacts of the microgenerators, implemented in Chapter 5.

4.3.5 Approach 4

Approach 4 relies on the EPS 2000, as described in Chapter 3.3.4. The EPS 2000's weighting procedure is based on the principle of willingness to pay (WTP) to restore impacts on the safeguard subjects, represented by environmental load units (ELU), where 1 ELU is equal to 1 Euro (in 2000). Appendix 4 presents the impact of 1kWh from the centralised systems (electricity, natural gas, and oil) using the EPS 2000 LCIA method. Table 4.7 below shows the impacts in terms of ELU from producing the microgenerators and the annual expected environmental benefits from reduced centralised energy couriers of electricity, natural gas and oil.

Impact category	Unit	Microwind production	Microwind Annual benefits			PV Production	BIPV Production	Annual benefits (PV & BIPV have similar outputs)		
			Min	Mean	Max			Min	Mean	Max
Life expectancy	ELU	113.090	15.548	49.009	85.399	908.561	521.617	73.231	96.891	112.664
Severe morbidity	ELU	30.554	5.597	17.642	30.742	269.111	148.147	26.362	34.879	40.557
Morbidity	ELU	2.407	1.132	3.568	6.218	35.485	30.007	5.332	7.055	8.203
Severe nuisance	ELU	3.418	0.074	0.234	0.408	77.577	67.402	0.350	0.463	0.538
Nuisance	ELU	1.290	0.353	1.113	1.939	14.961	12.965	1.663	2.200	2.559
Crop growth capacity	ELU	0.123	0.046	0.146	0.255	2.045	1.966	0.219	0.289	0.336
Wood growth capacity	ELU	-0.547	-0.277	-0.872	-1.519	-8.688	-7.045	-1.303	-1.724	-2.004
Fish and meat production	ELU	-0.026	-0.008	-0.024	-0.041	-0.376	-0.475	-0.036	-0.047	-0.055
Soil acidification	ELU	0.032	0.010	0.030	0.052	0.394	0.350	0.045	0.059	0.069
Prod. cap. irrigation Water	ELU	0.043	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Prod. cap. drinking water	ELU	0.433	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Species extinction	ELU	0.605	0.217	0.684	1.192	9.380	8.053	1.023	1.353	1.573
Total		151.42	22.69	71.53	124.65	1308.450	782.99	106.89	141.41	164.44

Impact category	Unit	SHW Production	SHW displacing natural gas annual benefits			SHW displacing oil annual benefits			SHW displacing electricity annual benefits		
			Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
Life expectancy	ELU	153.261	19.604	27.430	35.273	25.91	36.26	46.64	40.390	56.332	72.274
Severe morbidity	ELU	47.426	9.162	12.819	16.484	11.20	15.67	20.16	19.488	27.274	35.082
Morbidity	ELU	3.504	1.625	2.274	2.924	2.19	3.06	3.94	3.942	5.516	7.096
Severe nuisance	ELU	1.290	0.052	0.073	0.094	0.08	0.11	0.15	0.259	0.362	0.466
Nuisance	ELU	1.208	0.115	0.160	0.206	0.38	0.53	0.68	1.229	1.721	2.213
Crop growth capacity	ELU	0.192	0.063	0.088	0.113	0.08	0.11	0.15	0.162	0.226	0.291
Wood growth capacity	ELU	-0.787	-0.375	-0.525	-0.675	-0.55	-0.77	-0.99	-0.963	-1.348	-1.734
Fish and meat production	ELU	-0.045	-0.004	-0.006	-0.008	-0.01	-0.01	-0.02	-0.026	-0.037	-0.047
Soil acidification	ELU	0.031	0.003	0.005	0.006	0.01	0.01	0.02	0.033	0.046	0.060
Prod. cap. irrigation Water	ELU	0.001	0.000	0.000	0.000	0.00	0.00	0.00	0.000	0.000	0.000
Prod. cap. drinking water	ELU	0.012	0.000	0.000	0.000	0.00	0.00	0.00	0.000	0.000	0.000

Species extinction	ELU	0.850	0.347	0.485	0.624	0.46	0.65	0.84	0.756	1.058	1.361
	Total	206.94	30.59	42.80	55.04	39.75	55.64	71.56	65.3	91.2	117.1

Table 4.7 EPS2000 LCIA results for the assessed microgenerators; Approach 4 environmental inputs

Significant annual benefits are recorded by the EPS2000 given the fact that this LCIA methodology is the most comprehensive one (in terms of environmental impact categories) used for the analysis of microgenerators as explained in Chapter 3.3.4.

Annual environmental quantified benefits of approximately 72, 141, 141, 43, 56, and 91 ELUs (or Euros 2000 value) are achieved under the mean energy output cases for the microwind, PV, BIPV (similar output as PV), and SHW displacing natural gas, oil, or electricity, respectively. Over the entire lifetime of the system, the net benefits (i.e., including the production environmental impacts) amount to 922, 2217, 2742, 863, 1183, 2073 ELUs, respectively through the same sequence.

4.4 Energy and LCA output; conclusion

The expected energy output of the assessed microgenerators are obtained and/or verified from literature sources, including work done by Allen *et al.* (2008a and 2008c). Table 4.8 summarises these findings.

Microgenerator	kWh per annum		
	Min	Mean	Max
Microwind	276	870	1516
PV/BIPV	1300	1720	2000
SHW	647	813	978

Table 4.8 Summarised energy outputs

The CBA uses the energy outputs in Table 4.8, as would the financial appraisal with the exception of SHW, where the displaced energy couriers (natural gas, oil, or electricity) would be used, as indicated in Table 4.2. It is important to note that minimum, mean, and maximum are based on the resource availability in the UK. It could be that most of the systems are installed in their respective maximum category, or their respective mean category, yet this is not taken into account.

With respect to the LCA, approaches 1 and 2 are based on the LCI, while approaches 3 and 4 are based on alternative LCIA methods. These results form the quantified environmental impacts that are monetized through the 4 approaches (or adopted as in the case of the EPS2000 where results are given in monetary units) in the cost-benefit analysis (CBA) of Chapter 5.

Approach 1 (Table 4.4) has shown that substantial CO₂-equivalent savings are to be expected from the operation of the microgenerators over their 15-25 year lifetime. Approximately 25 tons of CO₂-equivalent for PV and BIPV and 15 tons of CO₂-equivalent for SHW in the mean output case are expected. SHW displacing oil and natural gas, and microwind displacing electricity are expected to save more than 10.6, 8, and 7.5 tons of CO₂-equivalent, respectively.

Approach 2 (Table 4.5) has added to approach 1 the impacts from sulphur dioxide (SO₂), nitrogen oxide (NO_x), large particular matter (PM₁₀) and other airborne pollutants. The significance of the pollutants cannot only be known when the damage value estimates of the respective pollutants, as outlined in Chapter 3.3.2, are factored in.

Approach 3 (Table 4.6) has expressed the environmental impact implications from the production of microwind, PV, BIPV and SHW systems in DALYs and PDF/m²/yr. The mean (energy output) total environmental benefits for the systems are 0.005, 0.0166, 0.0026, 0.0048, and 0.0097 DALYs for microwind, PV and BIPV, and SHW displacing natural gas, oil and electricity, respectively. The total PDF/m²/yr benefits of the systems, within their mean output assumptions, equate to 153, 506, 76, 172, and 295 PDF/m²/yr for the same sequence of technologies as above. The significance of the total environmental damages caused from the production and installation or reduced through the operation of the systems would become apparent once the damage estimates for DALYs and PDF/m²/yr are factored in. This has been done in Chapter 5.

Approach 4 (Table 4.7) uses monetary terms directly. Over the entire lifetime of the system, the net benefits (i.e., including the production environmental impacts) amount to 922, 2217, 2742, 863, 1183, 2073 ELUs, respectively through the same sequence.

5 Cost-Benefit Analysis (CBA) of Microgenerators

A CBA is carried out on the three microgenerators. Analyses of the capital (and installation) costs of the systems are reviewed first, followed by a discussion on and valuation of the expected direct and indirect benefits of these systems. Net results are presented through the use of the net present value (NPV) and the benefit-cost ratio, and sensitivity analysis is applied to the most important parameters. A CEA is also implemented via the levelised cost indicator to better situate the microgenerators within the context of energy supply options in the UK.

5.1 Costs of microgenerators

The capital and maintenance costs of the three assessed microgenerators are provided in this section separately for each system. These costs are obtained directly from correspondences with the system's manufacturers (and/or suppliers). However, costs are then compared to current literature sources in order to obtain the most representative cost range for the UK context.

5.1.1 Microwind

The capital (with installation) cost for the assessed 600W micro-turbine system, including a 10 meter steel tower, is approximately £4,397 (excluding taxes and/or subsidies) as indicated by the supplier of the system. This cost estimate includes; site survey, interconnect units and grid-tie inverter, mast pole, other miscellaneous parts, and installation.

In comparison to literature resources, the total cost of the adopted 600W system appears to be at the higher end of the scale. Table 5.1 indicates several system cost estimates from various literature (and supplier based) sources;

	Literature source	Capital cost per kW
1	(EST <i>et al.</i> , 2005)	£3,000
2	Alternative supplier A ³⁰	£4,000
3	Alternative supplier B ³¹	£3,360
4	(EE & EST, 2007)	£3,200
5	(Bergman <i>et al.</i> 2009)	£1800

Table 5.1 Indicated capital costs from literature sources for microwind systems

The 600W turbine is considerably smaller than the quoted literature sources in Table 5.1 and therefore the higher costs (per kW capacity) of the system represents its inferior position with respect to larger capacity turbines (when taken on a £/kW basis) and other microwind turbines in the UK. Chapter 5.6 revisits microwind systems using values adopted from Bergman *et al.* (2009). The 600W assessed microwind supplier indicated that these costs differences are not as large as indicated, however,

³⁰ Supplier unnamed for confidentiality purposes.

³¹ Supplier unnamed for confidentiality purposes.

due to how these microwind systems are power-rated with respect to wind speed. For example, a 1kW microwind system could be really a 600W system when the actual power curves are compared. Nonetheless, there are economies of scale with wind power, the larger the turbine the cheaper (on a cost per kW basis). A range of capital costs, specifically £3,000 - £4,400 (with a mean of £3,700), will be adopted in the analysis in order to make the cost of the microwind system more representative (and therefore the assessment here more generally applicable) of similar sized systems currently available in the UK.

The inverter life-time is assumed to be anywhere between 10 – 15 years (Antony *et al.*, 2007) depending on several factors, particularly heat (i.e., where it is installed), and therefore the assumption adopted is that the inverter will last as long as the 600W turbine and would not need changing or maintenance before then. With respect to maintenance costs, the 600W system supplier indicated that maintenance costs are based on 2 visits over the entire life of the turbine, with one visit involving electronic related maintenance and the other involving mechanical related issues. This is worked out to be approximately £40/year (Allen *et al.*, 2008a). This maintenance cost value is not far from literature quoted values that have placed maintenance cost at around £50/kW/year (see, for example, EST *et al.*, 2005).

5.1.2 PV & BIPV

A fully installed 2.1 kWp mono-crystalline PV system (or BIPV) was estimated to cost £10,442 (exclusive of any taxes and/or subsidies) fully installed (Allen *et al.*, 2008a). This cost, adopted directly from correspondences with the PV (and BIPV) supplier, is more or less within the indicated capital and installation costs from various literature sources, as shown in Table 5.2.

	Literature source	Capital cost (£/kW)
1	(Enviros 2005)	4,450
2	(EST <i>et al.</i> , 2005)	4,000-6,000
3	(Boyle, 2004)	5,000-5,500
4	(EE & EST, 2007)	5,000

Table 5.2 Indicated capital costs and life-years of PV

Literature sources indicate that maintenance costs could be between £50 - £90/kW/yr (Enviros, 2005; EST *et al.*, 2005). However, the maintenance costs of the PV system were assessed to be near zero (Allen *et al.*, 2008a), it would simply be beneficial for the owner to wash the panels periodically to remove any build up of dirt. Yet the maintenance costs quoted in the literature most likely accounts for the change of the PV (or BIPV) inverter required midway through the PV (or BIPV) 25-year estimated lifetime. A report on inverters by the National Renewable Energy Laboratory (NREL) indicates a 10% experience curve percentage (see Chapter 7 for an explanation of experience curves) for inverters, keeping in mind that there are many uncertainties with respect to future growth of inverter sales (NREL, 2006). Adopting the NREL's assumption of a 20% annual growth rate in the sales of inverters and the current cost of an inverter being £1,000 (DTI, 2007), at the end of year 12, the cost for an inverter will be approximately £650 per kW (Hammond *et al.*, 2009). This is an

approximation, and it is important to further indicate that an inverter size has an important impact on cost, for example, a 3kW inverter is about 50% cheaper than a 1 kW unit on a £/kW basis (NREL, 2006).

The capital (installed) costs of the PV (and BIPV) system will be assumed to be (net of subsidies or taxes) in the range of approximately £10,000 - £12,000, with a median value of £10,500³². Similarly, maintenance costs are solely the inverter replacement in year 13 at £650.

An economic benefit arises from the reduced need for concrete roof tiles in the case of the BIPV system only. Over 20 m² of concrete roof tiles were avoided due to the installation of this system, yielding, at £10 /m² of tiles, a net benefit of just over £200 (Hammond *et al.*, 2009a and 2009b). This cost saving will be reduced from the capital cost range obtained for the PV system above.

5.1.3 SHW

The capital (with installation) cost of a flat-plate SHW system depends on its type (i.e., manufacturer), size, and often on the time of purchase (in the summer time the costs tend to go up due to higher demand). The UK Solar Trade Association quotes a range of £2,500 - £4,000 (STA, 2009), while the Energy Saving Trust (EST) and Element Energy (EE) quote approximately £3,100 (EE & EST 2007; EST *et al.*, 2005). The manufacturer of the SHW system assessed in this paper indicates a range consisting of £3,000 in the off-season (winter) and £3,500 in the peak season. This range will be used in the analysis (i.e. £3,000 - £3,500). The maintenance costs of the SHW system are taken to be negligible (Allen *et al.*, 2008a). If the SHW system is installed in an area with hard water, a lime scale remover may be required. However, this would benefit the entire domestic water supply for the building and would therefore not be considered to be part of the maintenance costs. These cost estimations have been adopted in Allen *et al.* (2008a and 2009).

5.2 Benefits

In Chapter 2.4.1, step 4 of the CBA process (Figure 2.5) requires the quantification and monetization of impacts. Yet estimating the direct and indirect benefits of the three microgenerators is the more problematical part of CBA. Two main components of benefits are relevant in the analysis; the value of electricity and hot water to UK households and the environmental benefits enabled over these systems lifetimes as quantified through the LCA in Chapter 4.

³² A main problem in the UK for PV (or BIPV) is that of capital costs in an international context. As the main cost of the PV system are the PV modules or cells, and these are mostly imported (IEA, PVPS, 2009), the exchange rate plays a significant part in the price of PV systems in the UK. As an illustration, the exchange rate was £1 = \$2 when this research began late 2006, and yet the exchange rate reached £1 = \$1.5 in mid-2009. For a module cost particular to PV monocrystalline of \$2,500 per kW for example, in early 2006 this would correspond to PV module cost in the UK of £1,250/kW, while currently it stands at £1,667, or an increase of over 33%. For our assessed 2.1 kWp system, that is a difference in cost of almost £900. It is hoped that the range of capital costs may also capture this variation.

5.2.1 The value of electricity and hot water

Chapter 2.4.1.4 and Figure 2.6 show that the value of a good or service is really the willingness to pay (WTP) for that good or service, which in turn could be estimated by adding what is currently being paid with the consumer surplus. However, estimating the consumer surplus for electricity and hot water is problematic, and proxy values from alternative approaches are required.

5.2.1.1 The value of electricity

Beginning with electricity, measuring the WTP for electricity relies critically on a reliable estimate of the electricity demand function.

The demand for electricity was theoretically derived by Choynowski (2002). Choynowski (2002) indicated that the slope of the demand for electricity is negatively sloped with respect to its price with an upper bound (and lower) bound because electricity is really an input in the operation of electrical appliances. Therefore, for a given-stock of appliances, there is a maximum power needed (even if the price of electricity is zero), whereas the stock of appliances may change depending on consumers incomes, prices of other energy forms, and consumer tastes and preferences (Choynowski, 2002).

The total WTP (i.e., an indication for value) is the area under the demand curve up to the current price-quantity combination of electricity consumed and paid for by the UK householder. The annual average quantity of electricity currently consumed in the UK domestic sector is estimated to range between approximately 4,500 – 4700 kWh per household (DECC, 2008a). However, the UK government ‘Quarterly Energy Prices’ (DECC, 2009a) publications use an annual average domestic electricity use of approximately 3,300 kWh to calculate the average price of electricity paid (per kWh) on standard tariff. In the analysis below, the standard electricity tariff structure is assumed where the electricity tariff is applied the same regardless of time-of-use. The standard electricity tariff structure would be more common in households that use natural gas, oil or other non-electricity energy source for heating purposes. However, after communications with the Department of Energy and Climate Change (DECC), it was revealed that 3,300 kWh has not been changed for some time due to the fact that the ‘Quarterly Energy Prices’ publications and statistics related to domestic household prices are prepared to allow for a comparison of average energy bills over time (among other motivations) – therefore holding quantity constant is necessary (Reed, *pers. comm.*, 24th July 2009, reproduced in Appendix 7). A quantity of 4,000 kWh of electricity consumed annually by a standard tariff UK household is more likely, given that just under 20% of households in the UK are under Economy 7 tariff structure, which is opted for by households that use electric night storage heaters (Reed, *pers. comm.*, 24th July 2009). Therefore, the 4,200-4,700 kWh range is the representative range of an average UK household overall, yet 4,000 kWh annual electricity consumption could be considered as more representative of average households that use standard electricity only.

The latest average prices under standard tariff in England are approximately 12 p/kWh according to (DECC, 2009a). This estimate was used as a conservative proxy

for the value of electricity in Allen *et al.* (2008a and 2009) and Hammond *et al.*, (2009a and 2009b), and yet is found to be lower than the amount charged by several surveyed UK energy suppliers. The accurate estimate for electricity value is obtained only when accounting for the consumer surplus over and above the current average price for electricity. This was not implemented in the above mentioned references by the author given purely to the limitation posed by the ‘integrated appraisal’, where many perspectives and themes had to be included in one paper with word limits, preventing therefore the inclusion of consumer surplus included through the below discussed rationale.

The consumer surplus (CS) for electricity demand cannot be precisely calculated due to the many uncertainties involved, particularly the elasticity of demand for electricity. The demand for electricity is – according to many studies - inelastic but not perfectly inelastic in the long-run (where electricity-consuming stock adjustments could occur) (Lijesen, 2007; Narayan *et al.*, 2007). In the UK, studies have indicated that the long-run income elasticity is between 0.24 - 0.5, while it is quoted to range from close to 0 to -1.5 for long-run price elasticity in some studies (Narayan *et al.*, 2007) and -0.39 to -0.73 in others (Fouquet, 1995). In other words, demand for electricity in the long run will increase only by 0.24-0.5% for every 1% increase in income and would on the other hand fall by close to 0% (but not zero) to 1.5% for every 1% increase in the price of electricity in the UK.

Two main approaches are implemented and compared for the calculation of ‘electricity value’; the first approach assumes a convex demand function with constant price elasticity (Choynowski, 2002), while the second approach assumes a linear demand curve (i.e., elasticity rises continuously and proportionally with price).

The first approach to calculating the WTP for electricity assumes a convex demand curve function; $P = KQ^{-\eta}$, where p is price, K is a constant, Q is quantity consumed and η is the price elasticity of demand (Choynowski, 2002; World Bank, 2008). If electricity was a final product, then calculating (via integration) the area beneath the demand curve between $q = 0$ to $q = 4,000$ kWh (assuming current price of 12.2 p/kWh) would give the total value of electricity that would range depending on the price elasticity of demand (η). If η is -0.39, the value of electricity is equivalent to approximately 20 p/kWh. If η is -0.73, then the value would be approximately 45.2 p/kWh. This shows how sensitive the value of electricity would be to the price elasticity of demand, therefore indicating the likely magnitude of uncertainty in the analysis.

However, and as just mentioned, electricity is not an end product in itself yet it is an input for household appliances, lighting and the like. It is therefore more accurate to assume WTP for electricity with an upper and lower limit for a given stock of electricity-consuming equipment, meaning a WTP for a minimum amount of electricity per year (10s or 100s of kWh) are needed to satisfy the most basic of needs (Choynowski, 2002). This amount is difficult to pinpoint and therefore a proxy retrieved from the domestic electricity tariff structure of UK energy suppliers is used. In particular, almost all UK energy suppliers price the first couple hundred kWh of electricity at a rate higher than the remaining electricity use. This is a form of second-degree price discrimination, where the price per unit of output is not constant but depends on how much you buy, and is based on the supposed demand curve for

electricity as thought by the energy supplier. In other words, the energy supplier is trying to collect as much as possible from the consumer surplus by estimating their willingness to pay for each unit of electricity.

Most UK energy suppliers have their own price structures for standard tariff. Specifically, standard tariff is divided into two segments; the first covering a certain range of electricity consumption per year charged at a higher rate than the second segment which includes most of the electricity consumed. For example, some UK energy suppliers charge a higher price for the first 500kWh of electricity consumed, others for the first 728kWh or 900kWh and so forth. The energy suppliers also charge differently depending on the location (region) within the UK and depending on payment methods among other variables. However, given the competitive nature of the UK electricity sector (see OXERA, 2003), the average price differences should not (and are not) be significant. Figure 5.1 illustrates one sample from two current energy suppliers for the area of London wherefrom a better approximation for the value of electricity could be obtained.

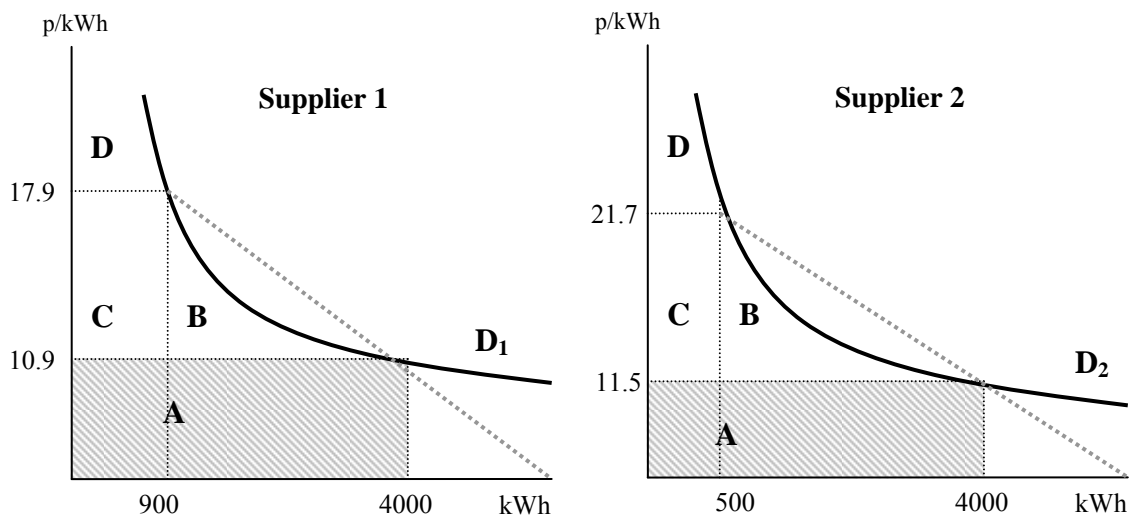


Figure 5-1 Domestic electricity tariff structures (assuming 4000 annual electricity consumption) for 2 UK energy suppliers

In Figure 5.1, areas A and areas C are calculated directly, however uncertainty ensues for areas B (and D) that depend on the shape of the demand curve that was assumed convex to the origin (D_1 and D_2) (Choynowski, 2002). The elasticity of demand can be calculated therefore through Equation 5.1 (World Bank, 2008).

$$\eta = \frac{\ln(P_{first}) - \ln(P_{remaining})}{\ln(Q_{first}) - \ln(Q_{remaining})} \quad 5-1$$

The elasticity (assuming constant elasticity) in the case of supplier 1 is approximately -0.33, while it is slightly lower at -0.31 for Supplier 2 (within the elasticity estimates indicated above), and within the indicated values by Narayan *et al.* (2007). Area B can be calculated from these values via Equation 5.2 (World Bank, 2008).

$$\begin{aligned}
B &= \int_{Q_{first}}^{Q_{rem}} K Q^{\eta} dQ - (Q_{remaining} - Q_{first}) P_{remaining} \\
&= \frac{K}{\eta + 1} (Q_{remaining}^{\eta+1} - Q_{first}^{\eta+1}) - (Q_{remaining} - Q_{first}) P_{remaining}
\end{aligned}
\tag{5-2}$$

Areas B for UK energy suppliers 1 and 2 are approximately £133 and £161 respectively. Total WTP is adjusted to equal area A, B and C. Area D is omitted from the analysis because a lower bound of minimum electricity consumption was assumed. Through Supplier 1, a UK domestic householders will be WTP approximately £632 per annum or 15.8 p/kWh (for 4,000 kWh), and Supplier 2 is WTP £673 per annum or 16.8 p/kWh.

If a linear demand curve is assumed (dashed line in Fig. 5.1), then total WTP will be £716 (17.9 p/kWh) and £868 (21.7 p/kWh) for Supplier 1 and 2 respectively (from $Q = 900$ or 500 kWh up to 4000 kWh). However, a linear demand curve has no theoretical basis (Choynowski, 2002), and therefore the assumptions and outputs under this method are not used in the CBA applied in this chapter.

In both cases, estimating the WTP for electricity is problematic and is based on the uncertain assumptions adopted on all parameters, specifically on the assumption of constant price elasticity, on the value(s) of price elasticity, and on the amount of total quantity consumed (4,000 kWh). Nevertheless, the values obtained give a more accurate indication for value of electricity than the (displaced) revenue proxy for total benefits.

5.2.1.2 The value of hot water

A similar analysis as that of electricity above is performed on gaining a value for hot water in the UK. Although the similar principles apply, more uncertainty and assumptions are required given the nature and different supply mechanisms for hot water. Two methods can be applied to obtain the value of hot water given an annual average consumption (from an average household of 2.4 persons) of hot water in the UK (excluding space heating) of approximately 1700 kWhth (Allen *et al.*, 2009).

The first method is to assume, as with electricity, a constant price elasticity for hot water combined with the price of hot water delivered to a UK household. Very few schemes deliver hot water directly to the UK household. However, some are present from combined heat and power (CHP) plants or other district heating schemes, and usually demand a maximum price of 3.5 p/kWh³³ according to correspondences with one of the companies (Veolia) applying a district heating scheme in Sheffield, where approximately 120,000 MWh of heat from waste incineration every year is delivered to households (Garrod, *pers. comm.*, 16th August 2008, reproduced in Appendix 7). With respect to price elasticity, literature sources on the price elasticity for domestic

³³ The price indicated was a range between 3 and 3.5 p/kWh. However, the correspondence with Veolia would not determine the exact amount due confidentiality concerns.

hot water demand were also lacking, with one exception being a study by Guertin *et al.* (2003). In an assessment covering 440 households in Canada, the price elasticity for hot water demand was estimated to be approximately -0.36 according to Guertin *et al.* (2003). Given these parameters, the value of hot water in the UK is approximately 5.5 p/kWh, calculated similarly through the function; $P = KQ^{-\eta}$.

An alternative method for determining the value of hot water is to take the overall UK national hot water delivery make up and assume it for a household. Specifically, if we assume that hot water from gas boilers account for approximately 85% of hot water delivered, while 10% and 5% of hot water are delivered electricity and oil respectively, a demand function for hot water could be constructed given the levelised cost of a gas, oil and electric boiler respectively, and given the annual domestic hot water demand of 1700 kWh_{th}.

Gas and oil boilers are used mostly (approximately 80% of their running time) to deliver space heating, in addition to hot water for bathing and other purposes (Utleay *et al.*, 2008). Therefore, only 20% of capital and maintenance costs for these systems would be apportioned or assumed (along with fuel use according to Chapter 4.2.3) in the levelised cost calculations. Figure 5.2 shows the levelised costs of the boilers on the vertical axis (as proxy for price paid for hot water), with each respective (85%, 10% and 5%) quantity of hot water breakdown consumed to total 1700 kWh_{th}. Levelised costs of a natural gas, oil and electric boiler amount to 13.5 p/kWh, 7.5 p/kWh, and 4.5 p/kWh respectively. However, given the many types and sizes of boilers, each with different possible levelised cost estimates, the cost values in Figure 5.2, which were obtained from various boiler models explored online, should be taken as tentative average values only.

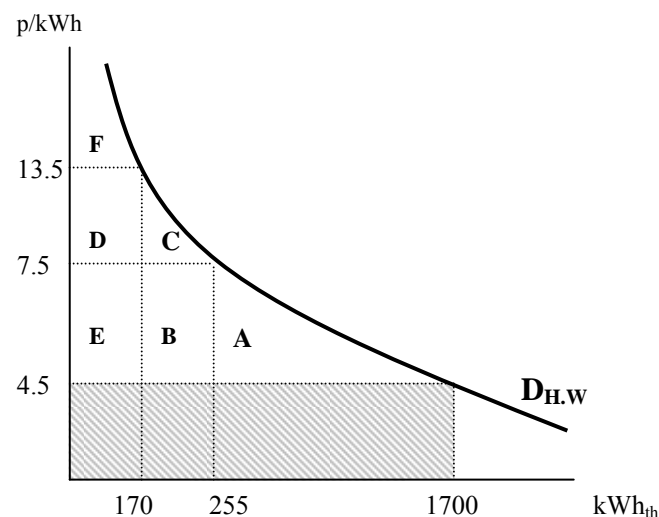


Figure 5-2 Constructed hot water demand function

The difference between Figure 5.2 and any of the two figures within Figure 5.1 is that there are two different price elasticities of demand assumed in the case for hot water; one calculated for quantity 170 to 255 kWh_{th}, and the other calculated for quantities consumed between 255 and 1700 kWh_{th}. Area F is neglected for similar reasons as in

Figure 5.1, due to the fact that a lower (minimum hot water use) bound is adopted, being 170 kWh_{th}, and given the fact that the price elasticity between quantity 0 and 170 kWh_{th} cannot be known through this procedure.

Area A in Figure 5.4 amounts to approximately £13, while Area C amounts to £2.2. The total WTP for hot water is approximately £110 or 6.5 p/kWh_{th}.

As with electricity, the assumptions and values adopted for the calculation of value for hot water is subject to considerable uncertainty. However, the omission of Areas D in Figure 5.1 and Area F in Figure 5.2 ensure a more conservative estimate of WTP which can also be argued to enhance the accuracy of the results, given that if only 1 kWh_(th) per annum of either electricity or hot water is delivered to a household, it could be considered worthless. Moreover, in Allen *et al.* (2008a), reproduced in Appendix 8, assumed a 6 p/kWh as the value of hot water based on the levelised cost of a natural gas boiler.

5.3 Environmental benefits

The environmental benefits of the assessed microgenerators are quantified according to the four options outlined in Chapters 3.3 and 4.3 through the LCA which forms the basis for approaches 1 – 4. The total environmental implications of applying these 4 approaches on the three assessed microgenerators are considered in this section in sequence.

5.3.1 Environmental benefits of microgenerators according to Approach 1

The social cost of carbon (SCC) was estimated in Chapter 3.5.1 to be valued at £71/tC (2009 value) and increased systematically in accordance with Kuik *et al.* (2007a). The corresponding net total benefits from the installation and use of the microgenerators are shown in Figure 5.3 (using 3% default discount rate), with error bars representing the sensitivity range of the SCC, i.e., £13/tC and £166/tC (2009 values), as ascribed to in Chapter 3.3.1.

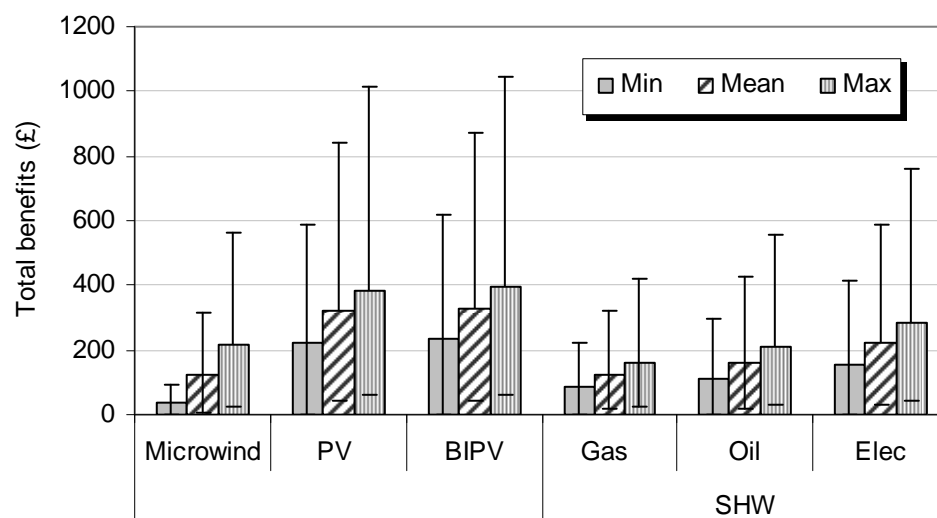


Figure 5-3 Total NPV of benefits from abated carbon emissions – Approach 1

Corresponding to the quantified carbon emissions outlined in Chapter 4.3.2 through the LCA inventory, Figure 5.3 shows that the BIPV system promises the most benefits in terms of carbon reductions, amounting to a net present value (NPV) of £330 in the mean energy output case (with mean SCC), followed by PV, and SHW displacing electricity with a mean value of benefits equal to £318 and £222 respectively. The SHW displacing gas and the microwind systems offer fewer benefits in carbon terms, yet still amount to a NPV of £121 and £122, respectively. Microwind under the high energy scenario delivers a net benefit of £217 under the mean SCC.

The values in Figure 5.3 make up the values as ascribed to through approach 1; the climate change focused approach. An endogenous social discount rate of 3% is used for the SCC. In the CBA, the default discount rate is 3%, and this rate has been applied on the already discounted SCC given that these reductions (or benefits) occur also in the future on a yearly basis over the microgenerators' lifetimes. An unavoidable discrepancy will occur in the sensitivity analysis, when discount rates are altered in order to observe their impacts on the CBA results. Discounting for the SCC is endogenous to the values adopted in the literature, and therefore no changing of the discount rate within the estimation of the SCC (or other environmental pollutant estimates for that matter) could be implemented.

5.3.2 Environmental benefits of microgenerators according to Approach 2

Approach 2 obtains the inventory for the selected airborne pollutants, as outlined by the ExternE and the NEEDS projects. Figure 5.4 shows the total benefits for the various microgenerators using the default discount rate of 3%.

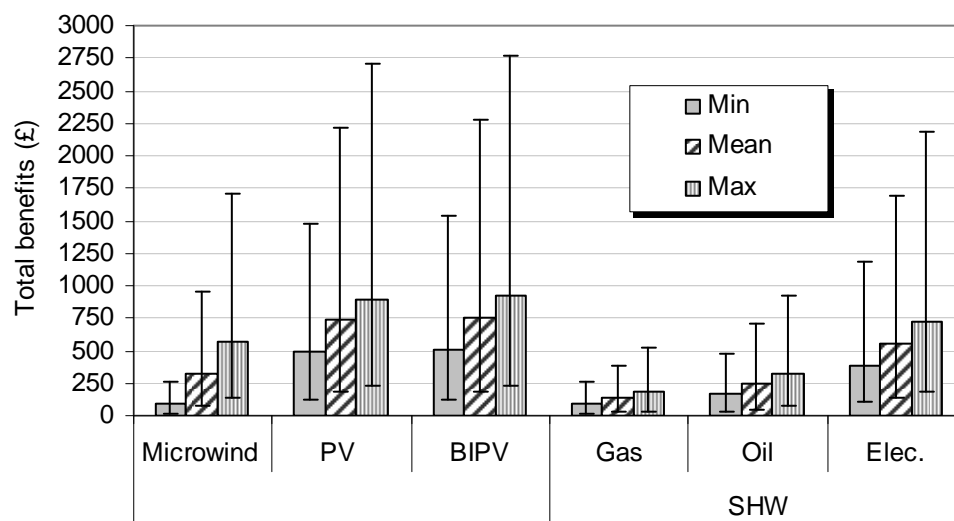


Figure 5-4 Total NPV of benefits from air-borne pollutants – Approach 2

The mean (i.e., using the mean values for the damage functions of air pollutants and mean energy output of the systems) expected total benefits from reduced environmental externalities are approximately £316, £735, £756, £140, £242, and £555 for microwind, PV, BIPV, and SHW with gas, oil, and electricity displacement, respectively. When comparing approaches 1 and 2 together, it can be seen that, on

average, greenhouse gas emission damages account for almost 40-43% of the total damages from air pollutants for PV, BIPV, microwind and SHW displacing electricity, while it accounts for 60% in the SHW displacing the oil case, and 85% for the SHW case displacing natural gas. However, and as seen from Figure 5.4, there are considerably uncertainties involved with respect to the damage function estimations, as evident from using a standard deviation of at least 3 (see Chapter 3.3.2).

5.3.3 Environmental benefits of microgenerators according to Approach 3

Approach 3 concentrates on the expected human health implications (using the DALY indicator) and the restoration costs for ecosystems (using the PDF/m²/year indicator) from the production and use of the three assessed microgenerators, as discussed in Chapter 3.3.3. A DALY has been estimated to range from £18,000 – £70,000 with an assumed mean of £30,000 (2009 value). Ecosystem quality on the hand was valued with an annual costs range of approximately £0.023-£0.31/PDF/m²/year (mean £0.17 PDF/m²/year), using 2009 values. These values are applied on the output estimates from the LCA using the EI-99 LCIA method in Chapter 4.3.4. The NPV of total environmental benefits in terms of health implications from running the microgenerators are presented in Figure 5.5.

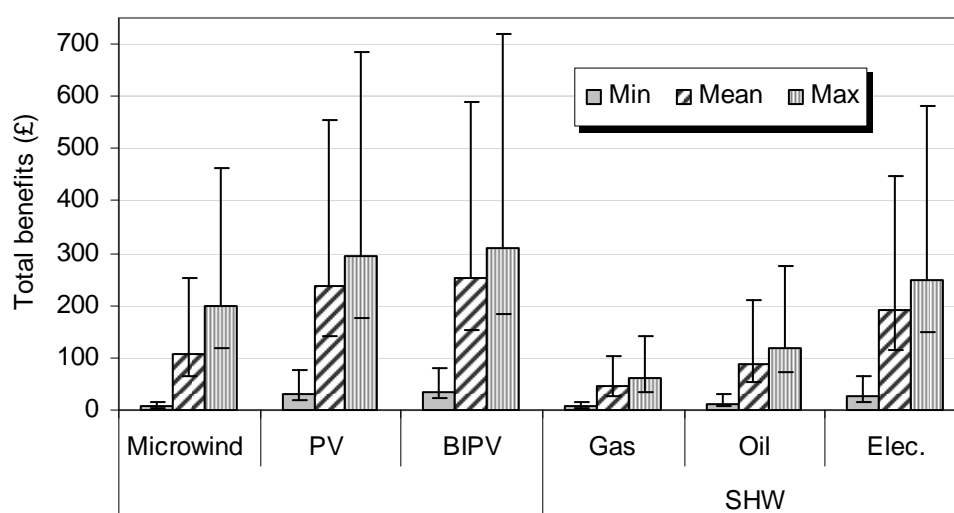


Figure 5-5 Total NPV of environmental benefits from Approach 3

Average damage benefits are indicated to be approximately £108 for microwind, £238 and £252 for PV and BIPV respectively, and £44, £90, and £191 for SHW displacing natural gas, oil, and electricity respectively. The minimum and maximum range for the values of DALY and PDF/m²/year, shown also by the error bars in Figure 5.5, will be imposed on the CBA results in the sensitivity analysis.

An important outcome in approach 3 was the fact that ecosystem quality, as measured through the PDF/m²/year, had very marginal impacts on the total environmental benefits and costs of the microgenerators, as the environmental impacts from production of the microgenerators often only slightly surpassed their respective total benefits or, oppositely, was only slightly surpassed by the total of the environmental benefits, respectively for each microgenerator. This was an indication that restoration

costs do not reflect damage costs, and tend to provide a lower estimate, as indicated by the NEEDS project itself (NEEDS, 2006a).

5.3.4 Environmental benefits of microgenerators according to Approach 4

The EPS2000 LCIA method provided estimates in Chapter 4.3.5 for the environmental impact benefits of the microgenerators according to environmental load units (ELU), where 1ELU is equal to 1Euro (2000 value). The values are updated from Euros (2000) to UK Sterling through a similar calculation as applied on the ExternE/NEEDS values in Chapter 3.2. The uncertainty factors, as listed in Table 3.12, will be applied as a minimum and maximum range for damage values. However, the uncertainty mode of 3 will be applied throughout, meaning the minimum range would be equal to the mean divided by 3 and the maximum range will be the mean multiplied by 3, similar to the standard deviation used in Approach 2. The results of the EPS2000 are presented in Figure 5.6.

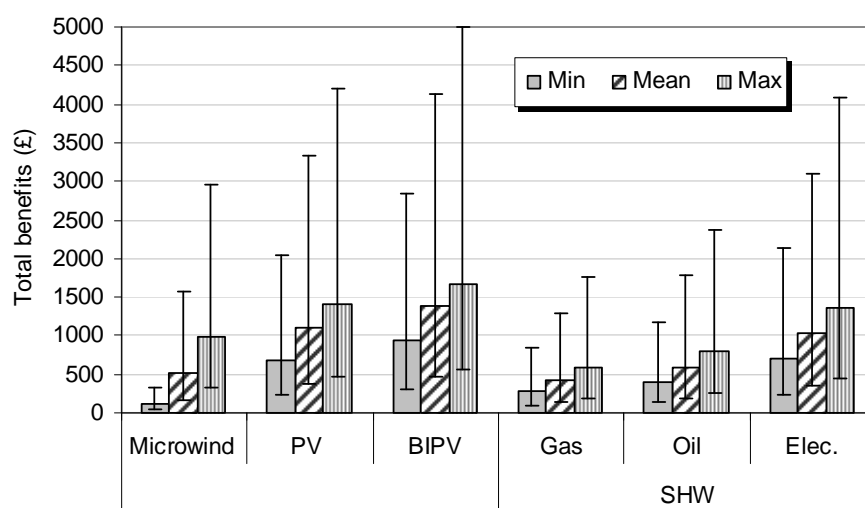


Figure 5-6 Total NPV of environmental benefits from Approach 4

Approach 4 has the largest recorded monetized environmental benefits from all the 4 approaches applied above. The mean benefits recorded by the EPS2000 reach £527 for microwind, £1,100 and £1370 for PV and BIPV respectively, and £430, £590, and £1030 for SHW systems displacing natural gas, oil, and electricity correspondingly. A large part of this difference is due to the difference of default values used by the EPS2000 of values, such as the Years of Life Lost (equal to DALY) of 85,000 ELU (Steen 1999a), which is from the ExternE project and is more than twice that of the DALY value adopted by the updated NEEDS project (and used in approach 3 through the EI-99 LCIA method). Also and as mentioned earlier, the EPS2000 has the most comprehensive list of impact categories between all the 4 approaches used.

5.3.5 Environmental impacts conclusion

The results of the environmental externality benefits, as experienced by the microgenerators over their lifetime, indicate significant differences depending on

which approach is adopted. The mean results of the four approaches are shown in Figure 5.7.

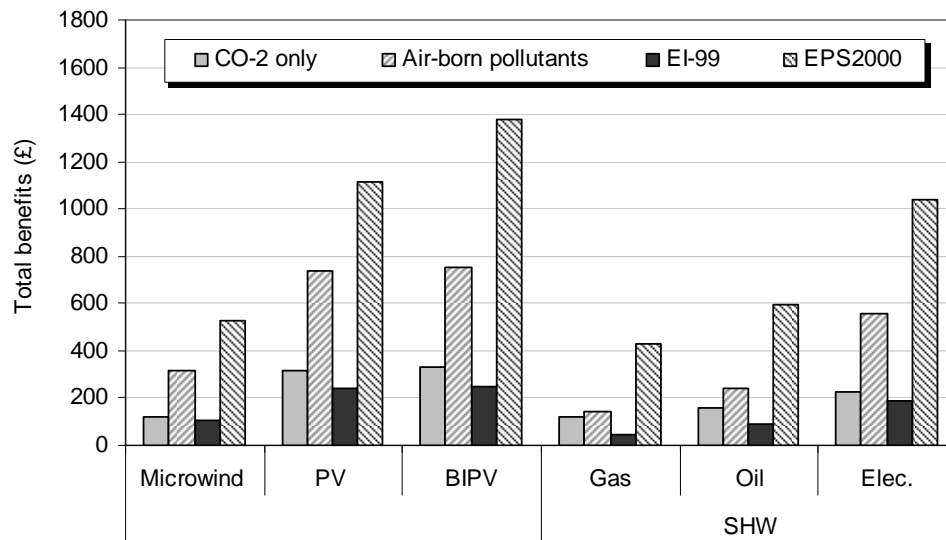


Figure 5-7 Total NPV of environmental impact benefits through four different approaches

Some of the reasons for these differences are self-evident, for example approach 2 is approach 1 in addition to other environmental air-borne pollutants – therefore an expected increase in environmental valuation estimates. The estimates according to approach 3 deliver the lowest estimates for the environmental externalities, primarily due to (1) the lower values for 1 DALY adopted by the NEEDS projects (and here), (2) due to insignificant contribution of ecosystem quality due to the use of restoration costs, and (3) due to the leaving out of other environmental endpoints. The EPS2000 covers most of the environmental impacts involved. It is based on values transferred from different literature sources, including the ExternE project, and it delivers the highest monetised environmental benefits relative to the other approaches.

5.4 CBA results

The results of the CBA are presented for each microgenerator separately below. Four possibilities are included for each system, given the four options for monetizing environmental impacts above.

5.4.1 Microwind

The NPV and the corresponding benefit-cost ratio (BC ratio) of the assessed 600W microwind system are shown in Figure 5.8 for several potential cases.

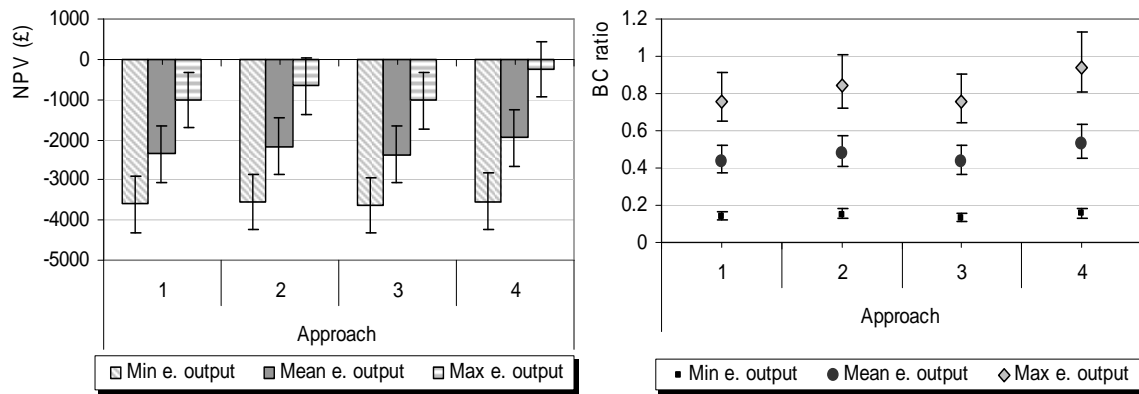


Figure 5-8 NPV and BC ratio of microwind under the 4 approaches

The NPV and BC ratio of microwind depends on the electricity output of the actual system, differentiated in Figure 5.8 by the separate bars (i.e., ‘e.output’), and on the assumed capital cost range (error bars) as assumed in Chapter 5.1.1. For low electricity output, all approaches experience an approximately similar NPV, amounting to a total loss of £3500 - £3600, or a BC ratio of 0.13 – 0.15. In other words, for every £1 spent on microwind in a low energy output regime, 13-15 pence should be expected only. For mean electricity output (i.e., 870 kWh per annum), a loss of approximately £2,360 for approaches 1 and 3 are recorded, reduced to £1,600 if low capital costs are assumed, while approach 2 and 4 experience a NPV of - £2,170 and - £2,000 respectively, reaching - £ 1,500 and - £1,250 for low capital costs. Only under an excellent wind regime or maximum electricity output would the microwind system experience a positive NPV of £37 and £455 for environmental monetization approaches 2 and 4, corresponding to a BC ratio of 1 to 1.13, under the minimum capital cost case respectively.

5.4.2 PV and BIPV

The CBA results for PV and BIPV systems are even less encouraging than those for the microwind system. The results all indicate to the current uncompetitive nature of solar electricity generation in the UK. Figure 5.9 presents the NPV and the BC ratio for the assessed PV system under the four adopted approaches of environmental impact valuation, under three solar irradiance (therefore electricity output) regimes, and for the range of expected capital costs of the system – given by the error bars.

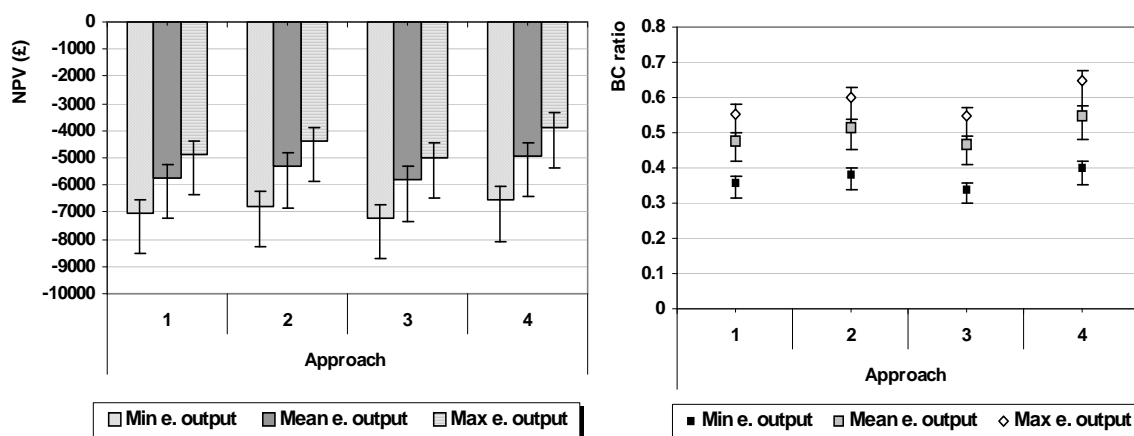


Figure 5-9 NPV and BC ratio of PV under the 4 approaches – (3% discount rate)

The mean electricity output case (solid grey coloured bar) for the PV system indicates that net losses amount to £5,700 - £5800 for approaches 1 and 3 respectively (a BC ratio of approximately 0.47), and net losses of £5,300 - £5,000 are observed through approaches 2 and 4 respectively (a BC ratio of 0.51- 0.54). These are reduced to losses amounting to £4,380 - £4,470 for approaches 1 and 3 under the maximum electricity case with minimum capital costs, and losses of £3,870 and £3,360 for approaches 2 and 4 under the same circumstances. In other words, the best case scenario sees a 58 pence return to a £1 invested through approach 1, 63 pence for approach 2, 57 pence for approach 3, and 68 pence return for approach 4.

The results for the BIPV system, shown in Figure 5.10, are slightly better than those for PV, although also not encouraging. Under the mean electricity output case, the NPV records a loss of £5,530 - £5,608 for approaches 1 and 3 (a BC ratio of approximately 0.48), improved to losses of between £5,000 and £5,100 in the lower capital cost case (BC ratio of 0.5), while a net loss of £5,100 and £4,480 is observed for approaches 2 and 4 (BC ratios of 0.52 – 0.54 respectively), reduced to net losses of £4,600 and £4,000 with the lower capital cost case (BC ratio of 0.55 and 0.61 respectively).

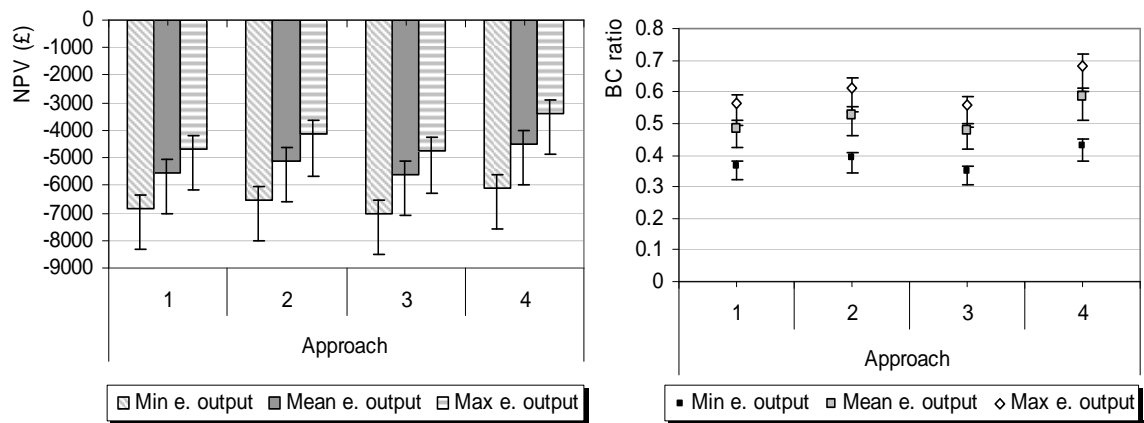


Figure 5-10 NPV and BC ratio of BIPV under the 4 approaches –

The best NPV case for BIPV occurs under the maximum electricity output case with lowest capital cost combination; registering a net loss of £4,170 and £4,260 for approaches 1 and 3, and a loss of £3,650 and £2,900 for approaches 2 and 4. In other words, for every £1 invested in a BIPV system, a return of 59, 64, 58 and 71 pence are expected for approaches 1, 2, 3, and 4 respectively.

5.4.3 SHW system

There are two possible approaches to implementing a CBA to a SHW system. The first approach, which is the one undertaken here, is to do an ‘absolute’ CBA, in that the value of hot water accounts for the benefits of a SHW system (as outlined in Chapter 5.2.1), along with the environmental externalities as presented by each of the four approaches, differentiated by the source displaced (i.e., gas, oil, or electricity), while the costs account for the capital cost of the system only. This CBA could be considered an average CBA for the SHW system in the UK, regardless of which original hot water generating source is present (i.e., gas boiler, oil boiler, or electric boiler). This approach was used to calculate the value of hot water in Chapter 5.2.1.

An alternative approach to CBA for a SHW system could be implemented separately for each case, i.e., the value of the benefits therefore would be differentiated by the energy source displaced (i.e., gas, oil, or electricity). A CBA following this route would then result in a difference in the value of hot water derived from the difference of original source of hot water deliver (i.e., type of boiler). This latter method is used in the financial appraisal of Chapter 6, without including the environmental impact benefits.

The results of the CBA for SHW displacing natural gas (i.e., the environmental benefits of displacing natural gas) are presented in Figure 5.11 (using again the default 3% discount rate).

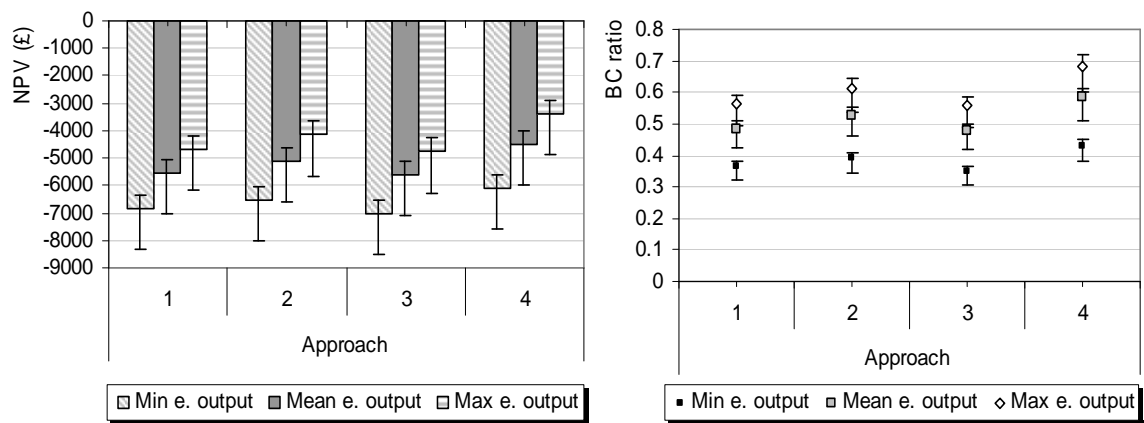


Figure 5-11 NPV and BC ratio of SHW displacing gas under 4 approaches –

In the mean energy (hot water) delivery case, a NPV of - £2,205 and - £2,280 are observed through environmental impact approaches 1 and 3 (BC ratios of 0.32 and 0.3 respectively), while also a NPV loss of £2,180 and £1,900 are observed for approaches 2 and 4 (BC ratios of 0.33 and 0.42 respectively). The best case for a SHW system displacing gas is under the maximum energy output case with minimum capital costs. The NPVs for the best cases registers losses of £1730 - £1830 for approaches 1 and 3 (BC ratios of 0.42 and 0.39 respectively), a loss of £1,700 for approach 2 (BC ratio of 0.43), and a loss of £1,300 for approach 4 (BC ratio of 0.56).

The results of the CBA for SHW displacing oil on the other hand (i.e., with the environmental benefits of displacing oil) are presented in Figure 5.12.

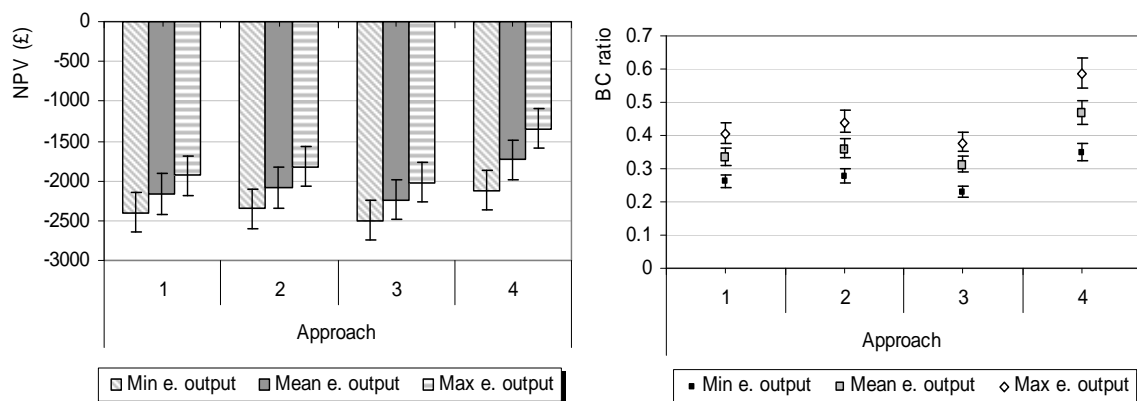


Figure 5-12 NPV and BC ratio of SHW displacing oil under the 4 approaches –

Results for the SHW system displacing oil are slightly better than those for displacing a natural gas boiler, due strictly to the environmental benefit differences between the two. The mean case energy output in Figure 5.12 records a NPV loss of approximately £2,160 for approach 1, £2080 and £2,237 for approaches 2 and 3, and a loss of £1,735 for approach 4 (corresponding to BC ratios of 0.33, 0.36, 0.31, and 0.47, respectively). The best case scenario, under maximum energy output with

minimum capital costs, registers a NPV loss of £1,680 and £1,570 for approaches 1 and 2, and a NPV loss of £1,750 and £1,100 for approaches 3 and 4 (corresponding to BC ratios of 0.44, 0.48, 0.41, and 0.63, respectively).

The CBA for a SHW system displacing electricity yields better results than those for the SHW displacing natural gas and oil, given the greater environmental externality benefits of displacing electricity. Figure 5.13 presents these results, indicating also a NPV loss and BC ratio smaller than 1 across all cases.

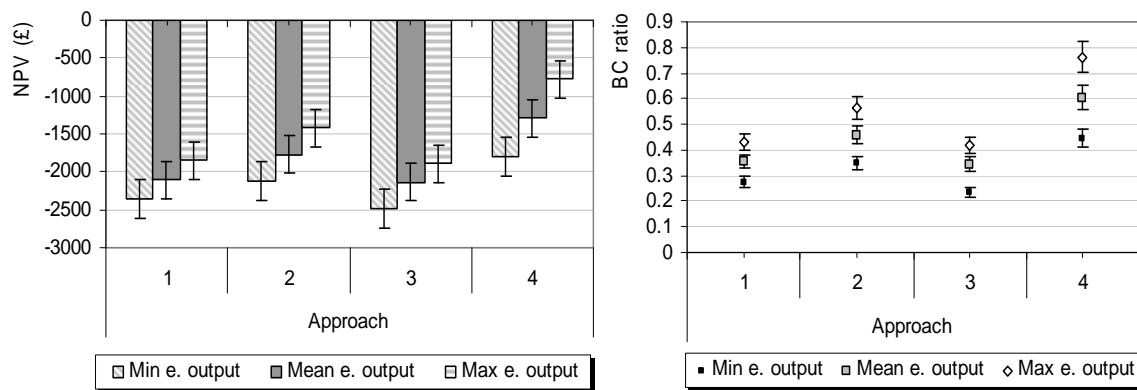


Figure 5-13 NPV of SHW displacing electricity under the 4 approaches –

The mean case scenario delivers a NPV loss of approximately £2,100 for approaches 1 and 3 (BC ratio of approximately 0.35), and NPV losses of £1770 and £1,300 for approaches 2 and 4 respectively (corresponding to BC ratios of 0.45 and 0.6). The maximum energy output scenario with minimum capital costs yields a NPV of £1,600 - £1640 for approaches 1 and 3, and NPV of - £1,172 and - £530 for approaches 2 and 4 respectively. This outcome corresponds to a return of 0.47, 0.61, 0.45, and 0.82 pence for approaches 1-4 respectively, on a £1 investment.

5.5 Sensitivity analysis

The main CBA analysis performed in Chapter 5.4 contained several parameters with respective ranges included. Three energy output options for the microgenerators pertaining to the possibilities in the UK were adopted in Figures 5.8 – 5.13 (i.e., min, mean, and max), the current (2008-2009) range of capital costs that may be found in the UK where internalised in the sensitivity bars in Figures 5.8 – 5.13 also, and similarly the environmental impact quantification and monetization were separated through the 4 approaches identified and applied in Chapters 3.5 and 5.3 respectively.

However, three other main parameters may have different possibilities; (1) the value of electricity and hot water, (2) environmental damage cost estimates, and (3) the discount rate used.

In Chapter 5.2.1, the value for electricity and hot water were derived through the construction of a demand curve for each by taking several assumptions with respect to the price elasticity of demand and the shape of the demand curve itself. In the financial appraisal of Chapter 6, the benefits will be in terms of the displaced cost of natural gas, oil, or electricity depending on the microgenerator at hand. The CBA

analysis adopted a mean value for electricity of 16.3 p/kWh, which is simply a 0.5 p/kWh difference between the minimum and maximum estimated values respectively. Hardly any notable change to the default CBA results will follow if the minimum and maximum range for the value of electricity is presented in the analysis within the identified minimum-maximum range. A similar conclusion can be made for the value of hot water, where the value of 6.5 p/kWh_{th} was assumed, a 1 p/kWh_{th} difference from the minimum range. Therefore, the value of electricity and hot water will not be altered in the sensitivity analysis.

The environmental externality benefits presented in Chapter 5.3 showed a significant range for each microgenerator depending on the environmental quantification approach adopted and the actual damage estimates within the approaches themselves (expressed through the error bars in Figures 5.3 - 5.6. Only the mean values in each environmental quantification approach were included in the default CBA. However, there is a possibility that the environmental damages have been either overestimated or underestimated. Therefore, a minimum environmental damage cost and a maximum environmental damage cost scenario is warranted. The changes will be expressed through the benefit-cost ratio for the sake of comparison between the default CBA and the changed environmental damage cost parameter within each approach, simplifying the presentation of the analysis.

Figure 5.14 shows the impacts of adopting either the minimum environmental damage estimates (therefore minimum overall benefits for the microgenerators), or the maximum environmental damage estimates for the microwind, PV, and BIPV systems, assuming mean capital costs.

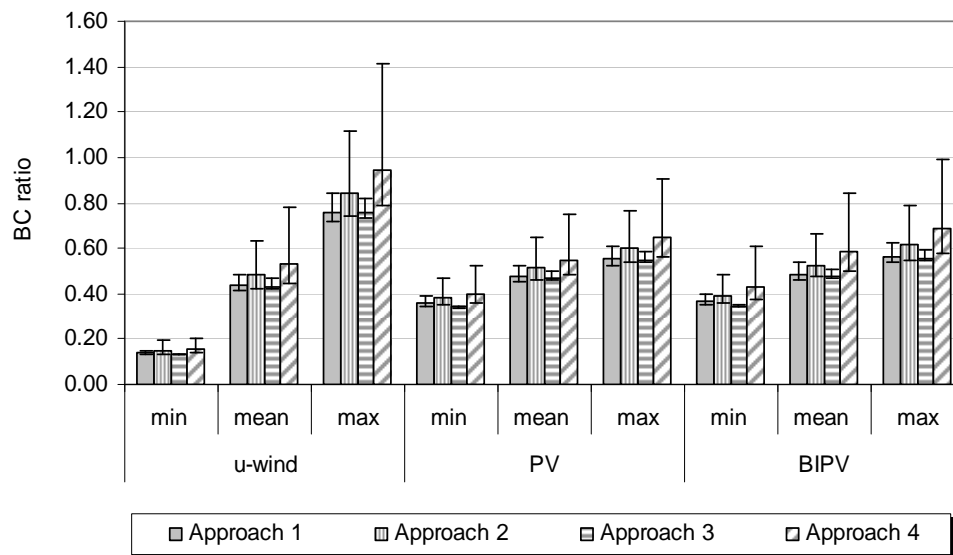


Figure 5-14 BC ratio for microwind, PV and BIPV when environmental damage functions are changed

The block bars' heights in Figure 5.14 represent the mean BC ratios, as expressed through the right hand schematics of Figures 5.8 - 5.10. The error bars in Figure 5.14 represent the adoption of alternative environmental damage functions, as expressed in Chapter 5.3 and Figures 5.3 – 5.6. Microwind will yield a BC ratio of over 1 under

environmental quantification approaches 2 and 4 (from a BC ratio of 0.84 and 0.94 respectively) with maximum energy output. Taking the higher end of the environmental damages will improve the overall BC ratio of microwind for the other categories, yet it will not suffice to break the target BC ratio of 1 for the minimum or average wind output regime. If the environmental damage estimates adopted are minimised, all the BC ratios will decrease, making the system even more uneconomic across all energy output and environmental externality approach cases.

With respect to the PV system, adopting the lower environmental externality benefits will slightly lower the BC ratio, yet adopting the higher environmental externality values will improve the economics more considerably. They will just fall short in achieving a BC ratio of at least 1 (through environmental quantification approach 4).

Adopting the higher values for the BIPV system on the other hand will enable the BC ratio to reach 1 under the maximum energy output case, and under the EPS2000 (approach 4) methodology and values. Improvements will occur across the other approaches and energy output assumptions, yet not enough to break the BC ratio mark of 1. Lower environmental damage estimates will lower the desirability of the BIPV system, which already faces BC ratios of below 1 in the mean output case under all the 4 approaches.

Figure 5.15 shows the same analysis for the SHW system displacing any one of the three adopted alternatives (i.e., gas, oil or electricity). With respect to the SHW system's mean assumptions, no approach or energy output yield assumption enabled a BC ratio of at least 1. However, adopting the higher environmental benefits will achieve BC ratios of more than 1 for four cases; (1) SHW displacing oil under the maximum output and environmental quantification approach 4, (2) SHW displacing electricity under mean electricity output through approach 4 as well, and (3) and (4) SHW displacing electricity under the maximum electricity output through approaches 2 and 4.

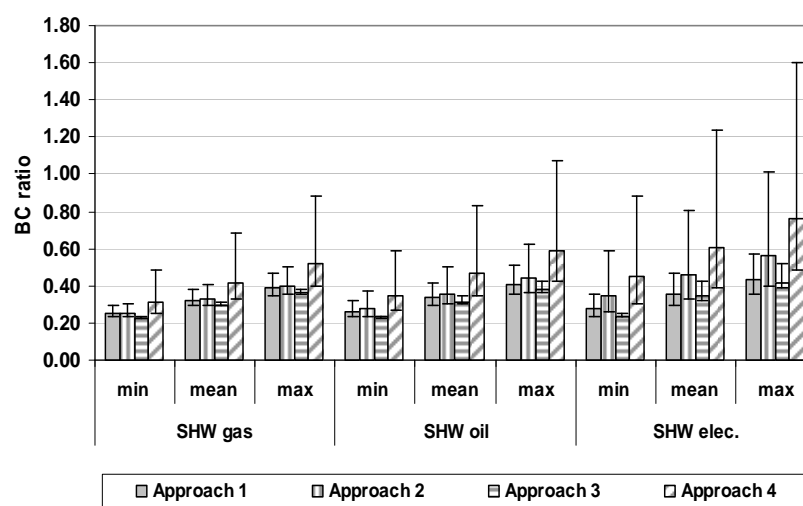


Figure 5-15 BC ratio for SHW displacing gas, oil, and electricity when environmental damage functions are changed

The final parameter that may be changed is the discount rate. From Chapter 2.4.1.5, two alternative discount rates were recommended to be adopted in order to cater for either the prescriptive or the descriptive viewpoints. The former will lend support to a lower discount rate, while the latter for a higher one. The discount rates of 1.5% and 5% would be applied to the analysis to assess whether any significant change to the results are encountered. As mentioned earlier, the discount rate changes will not affect the environmental damage values in themselves, particularly for the CO₂-equivalent case, given that these are from the literature. However, the environmental benefits experienced in future years will be discounted to the two ascribed discount rates of either 1.5% or 5%. Figures 5.16 and 5.17 show the BC ratios of the various microgenerators given the various energy outputs and approaches, where the lower-end error bars indicate the discount rate of 5% and the higher-end error bar indicates the BC ratios estimated through the 1.5% discount rate.

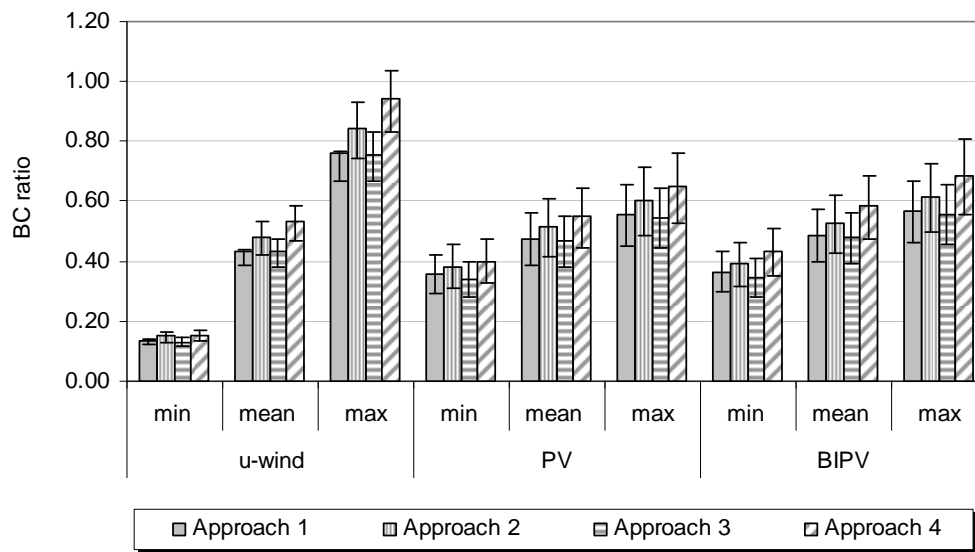


Figure 5-16 BC ratios for microwind, PV and BIPV under different discount rate regimes (1.5% or 5%)

Figure 5.16 shows that changing the discount rate from the assumed default value of 3% to either 1.5% or 5% will not change the results dramatically. Only in one case, the maximum output for microwind through approach 4, will the BC ratio reach at least 1 with a 1.5% discount rate. With respect to the SHW system, similar results are obtained where the CBA outcome will either improve slightly under the lower discount rate of 1.5%, or further slightly dampen under a 5% discount rate regime. This is shown in Figure 5.17.

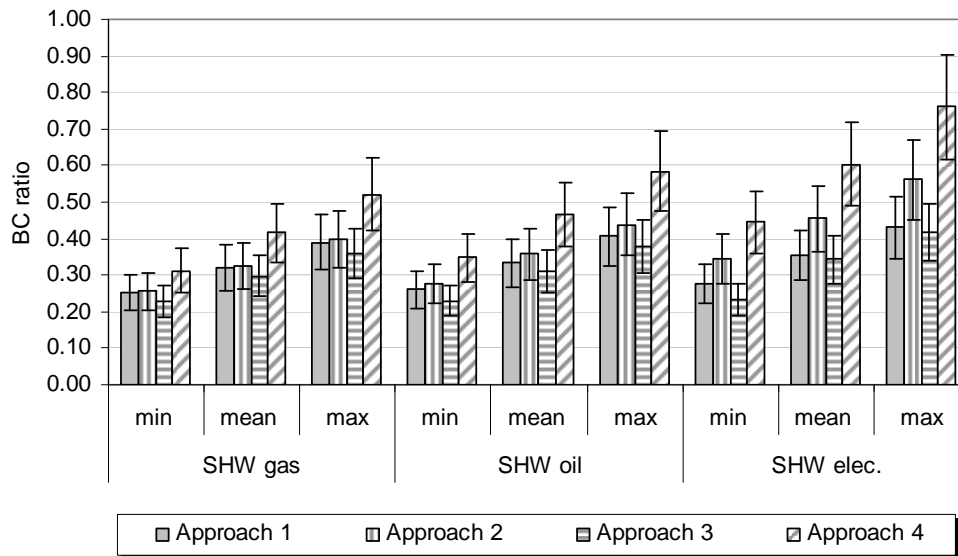


Figure 5-17 BC ratio for SHW displacing gas, oil, and electricity under different discount rate regimes (1.5% or 5%)

The sensitivity analysis above highlights the importance of hitting the mark when it comes to the monetization of environmental damages. However, the uncertainty in accurately monetizing these externalities has led to the adoption of the four approaches, and various damage estimates within each approach. Approach 4 could be considered the most complete, although the least accurate (recall that ‘methodology accuracy’ has been described to account for the robustness of the methodology used, particularly the linking of LCA and valued damage functions estimated through the NEEDS/ExternE projects), while approach 1 and 3 could be considered more accurate, although less complete, as mentioned in Chapter 3.5. Approach 2 seems to balance between accuracy and completeness.

5.6 Revisiting microwind; a better representation

Chapter 5.1.1 has indicated that the assessed microwind system’s capital costs are on the higher end of the costs of such systems available in the UK market. It is also rather a small system when usually larger systems of at least 1 – 1.5 kWp are better tailored for the electricity demand of UK households. A recent study has indicated that a 1 kW microwind system costs around £1715 without VAT (Bergman *et al.* 2009). It is therefore arguably more representative to take the cost and size (i.e., at least 1 kWp) of such a turbine as opposed to the analysed 600W microwind system assessed in this thesis.

Figure 5.18 shows the net-present value of a 1 kWp microwind system in the UK assuming a cost range of £1700 – £2000 (mean £1850). Figure 5.18 clearly indicates that microwind systems are highly viable options to consider in the UK.

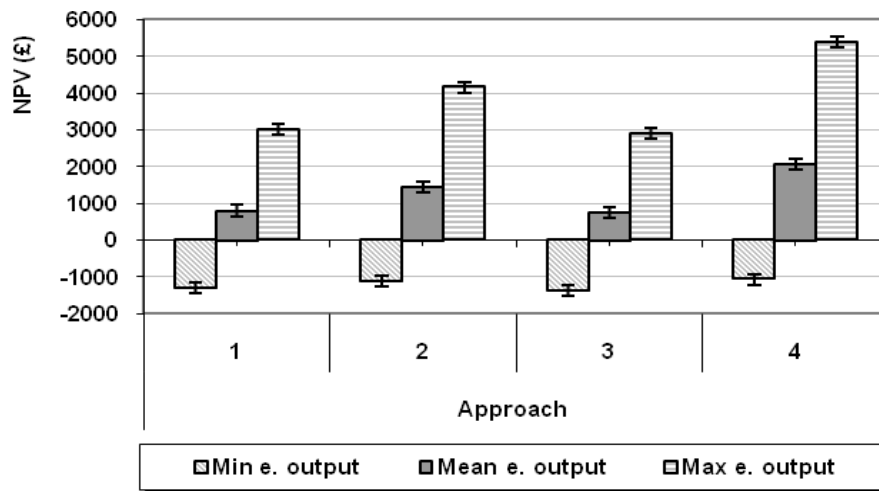


Figure 5-18 NPV of a 1 kWp microwind system – a better UK representation

Figure 5.18 highlights the fact that the assessed microwind in this thesis is not a representative choice of microwind systems in the UK. In fact, the benefit-cost ratio for more representative scales and prices of microwind in the UK amounts to 2-3 (i.e., for every £1 spent on these systems, a £2-3 return should be expected) depending on which environmental approach to adopt. Clearly, a different set of recommendations ensues from this realization, and only a recommendation for future research can be indicated to here.

5.7 CBA of microgenerators; discussion and conclusion

The default CBA results show that the microgenerators in the UK currently operate with a net total loss, with the exception of microwind which may yield a positive NPV (and/or a BC ratio of at least 1 or greater than 1) under a high wind regime (energy output) with low capital cost scenario. The analysis also shows the importance of environmental impact benefits in the economics of microgeneration. The percentage of environmental benefits to total benefits of installing and running these systems over their lifetime is shown in Figure 5.21 for the mean environmental damage cost estimates within each approach.

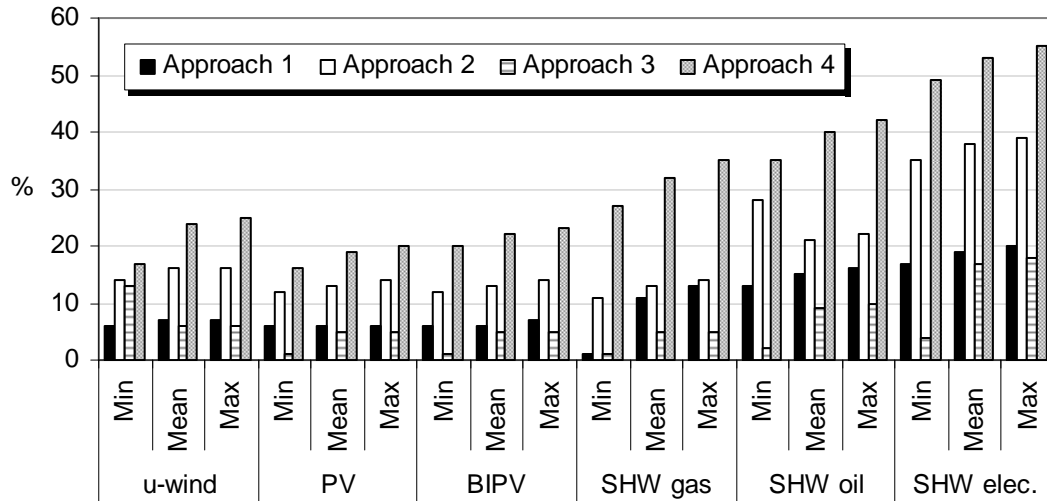


Figure 5-19 Percentage of total benefits of the three microgenerators attributed to environmental externality benefits

Environmental benefits can account up to 50% or more of total benefits for SHW applications next to an electric boiler. However in most of the cases outlined in Figure 5.21, the environmental benefits account to between 5 – 30% of total benefits, depending on the microgenerator, energy output case, and environmental quantification approach selected.

The sensitivity analysis has indicated that there could be situations where the economics of the systems can yield a positive NPV or a BC ratio of at least 1. These are pertained to (1) the impacts of higher environmental damage estimate assumptions for microwind via environmental quantification approaches 2 and 4 with a high wind regime, and (2) to the BIPV system with a high energy regime under approach 4.

Capital costs remain the main culprit for the poor results in the CBA of the assessed microgenerators. These are bound to change into the future however, as shall be discussed in Chapter 7. The relatively low solar irradiance in the UK also plays a key part for the SHW and the PV/BIPV system's economic performance. Properly locating a microwind system is also tantamount to its economics, given the implications of terrain and turbulence on the system's performance, over and above the actual wind speed of the locality.

In conclusion, the results of the CBA of the assessed microgenerators in the UK are not encouraging currently, nor are they cost-effective when compared to other generating sources (see cost-effective analysis of Chapter 8). The gap is reduced however if the network usage charges are included, and if environmental impacts are internalised.

Several omitted variables and possible future transformations may, however, lend support to renewable energy sources in general, and microgenerators in particular, as shall be described in Chapter 7.

From a strictly economic perspective based on the NPV and/or the BC ratio indicators, a 'no go' decision would be made for all the assessed microgenerators, with the exception of wind in a high-wind resource area. Furthermore, a more representative microwind system should be given the 'go-ahead' even in the mean output scenario – focusing again on the fact that the selected 600W microwind system in the UK biases the results for microwind in general for the UK negatively.

However, other important variables and parameters discussed in Chapter 7 could not be monetized, and they support the rationale for installing these systems. These parameters and the respective decision either to recommend these microgenerators or not are discussed in Chapters 7 and 8.

6 Financial Appraisal of Microgenerators

The cost-benefit analysis (CBA) of Chapter 5 is a society-wide perspective which has shed light on the overall economic performance of the assessed microgenerators. In doing so, it also has given a clear indication as to the feasibility of these systems to society in general through the inclusion of both consumer surplus and environmental impact benefits. However, it is really the individual householder or consumer who will decide whether or not to purchase and install a microgenerator, and therefore the personal financial arithmetic, including any taxes and/or subsidies available on the systems, play the key role at the end in that decision.

The energy and life-cycle assessments of the three microgenerators in Chapter 4 have shown that there are valuable net energy and environmental benefits to be achieved from purchasing and running these systems over their respective lifetimes. In Chapter 7, it will be shown that potential capital cost reductions are to be expected, particularly as more of these systems are purchased. It will also be shown that there are potential socio-economic and social benefits to be accrued from the systems, as well as implications on security of supply – if major uptake is realised. Given these realities and possibilities, a financial appraisal of the microgenerators is warranted in order to recognize the individual incentives present and/or necessary for enabling an increase in the deployment of these systems.

This chapter implements a financial appraisal on the three assessed microgenerators; 600 microwind, 2.1 kWp PV and BIPV, and the 2.8 m² SHW systems. The appraisal is carried out with simple assumptions such as assuming that capital costs to be made for the microgenerators are already present by the householder (therefore no loan or interest on loan), and all the values are in real terms to do away with the implications of inflation. The financial appraisal estimates first the net present value (NPV), BC ratio, and the payback times (years) of the assessed microgenerators. Attention will be turned next to the current financial support initiatives or mechanisms available (and/or to be available) in the UK, and the impacts of these support levels on the financial results. Potential implications on property values are discussed last, along with a general discussion on the implications of the financial appraisal, linking the results to the cost-benefit analysis of chapter 5.

6.1 Financial costs of the microgenerator

The financial costs of microgenerators are similar to those indicated in the CBA of Chapter 5. However, a Value Added Tax (VAT) of 5% is added on the price of the systems as purchased by householders. In the CBA, such transfers of money are not considered a cost, while in the financial appraisal they are. Table 6.1 presents the capital costs of the systems, inclusive of VAT.

Capital costs inclusive of VAT (£)				
#	System	min	mean	max
1	Microwind	3,150	3,880	4,620
2	PV	10,500	11,025	12,600
3	BIPV	10,300	10,825	12,400
4	SHW	3,150	3,415	3,675

Table 6.1 Financial costs of microgenerators

With respect to maintenance costs, the same values as applied in the CBA are adopted in the financial appraisal. Therefore, no maintenance costs are assumed for the SHW system, while maintenance costs in the form of a change of the inverter mid-way through the PV and BIPV systems' lifetime is assumed. For the microwind system, maintenance costs are assumed to be £40 per annum.

Similar to the CBA applied in Chapter 5, a more representative microwind system in the UK context is analysed through a financial appraisal in Chapter 6.3.2.

6.2 Financial benefits (returns) of the microgenerators

Only the direct benefits from installing the microgenerators were considered in the financial appraisal. These were in the form of displaced and exported electricity for the electricity-supplying microgenerators, and in the form of displaced natural gas, oil, or electricity use for the SHW system. For the electricity providing microgenerators, net metering will be assumed in the default financial appraisal, meaning export prices would be assumed equal to import prices. This is not unrealistic as some energy suppliers do offer net metering to customers that have installed microgenerators.

6.2.1 The price of electricity and heating fuel

The current average price of avoided electricity is 12.2 p/kWh according to (DECC, 2009e), although the surveyed UK energy suppliers had prices slightly higher than this (as mentioned in Chapter 5.2.1). The current standard electricity tariff structure in the UK, also as indicated in Chapter 5.2.1, is usually composed of two bands; the first priced at a higher value for the first several hundred of kilowatt hours (kWh) consumed, and the second band prices the rest of the electricity consumed at a lower value. The microwind and PV/BIPV systems will most likely displace electricity belonging only to the second lower-priced band of electricity, therefore assuming an average price of electricity will over-estimate the benefits involved. Figure 5.1 in Chapter 5.2.1 already shows two UK energy suppliers pricing their second band at approximately 10.9 and 11.5 p/kWh respectively (11.5 and 12.1 p/kWh inclusive of VAT) as of August 2009. Two other energy suppliers have their second band priced at 11.9 and 13 p/kWh respectively (inclusive of VAT). Therefore, assuming a 12 p/kWh price (inclusive of VAT) for displaced electricity could be considered accurate for the default financial appraisal, keeping in mind that there will be slight (i.e., 1 – 1.5 p/kWh) variations from this mean value between regions, UK energy suppliers, and payment methods. Net metering shall be assumed, i.e., exported electricity will receive the same price as that imported. This assumption was made also in Allen *et al.* (2008a) and Hammond *et al.* (2009a and 2009b).

The average price of natural gas is approximately 3.16 p/kWh (inclusive of VAT) according to DECC (2009f). This current price is within the range of four surveyed UK energy suppliers that have priced their second band of gas at 2.7, 3.3, 3.4 and 3.5 p/kWh respectively.³⁴ The price of 3.2 p/kWh is therefore an accurate estimate for the financial appraisal.

Oil is purchased in bulk and delivered individually to homes by trucks or other vehicle means. The price of oil purchased depends also on the region, the supplier, and the quantity purchased where the more oil purchased, the lower the price per unit. On average, an on-line survey of six oil suppliers indicated that oil prices delivered to UK homes are currently approximately between 35 and 43p/litre³⁵ for quantities ranging from 500 – 2000 litres. In 2008, delivered oil prices however reached approximately 58p/litre. One litre of burning oil contains around 10.3 kWh (Carbon Trust conversion factors), therefore the current price of oil ranges from 3.4 to 4.2 p/kWh, down from 5.6p/kWh a year earlier. A current price of 4.5 p/kWh will be assumed in the analysis, given the range within the time frame of the past 1-2 years.

It is important to reiterate that electricity and domestic heating fuel prices are constantly changing, and changing with them are the benefits of installing a renewable microgenerator. Figure 6.1 shows the real (1990 = 100) retail price index of electricity and fuels over the past 20 years and up to the first quarter (Q1) of 2009. What is evident is that prices do change and are on average increasing with the exception of the current trend of prices within the economic climate of global recession (at the time of writing 2009).

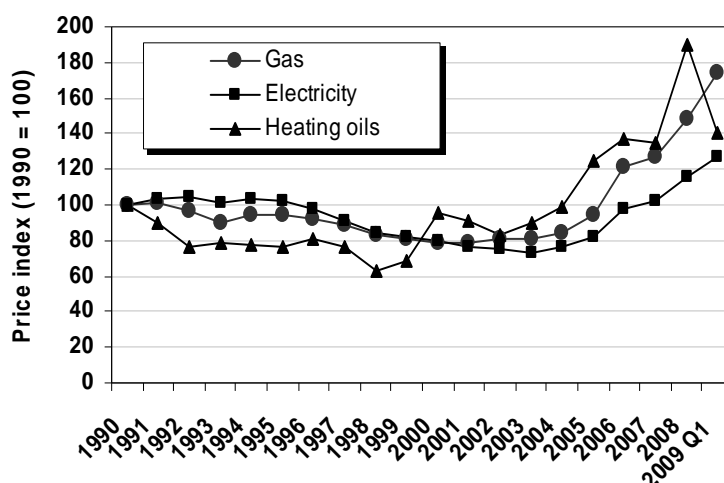


Figure 6-1 Retail price index for fuel components
(Source: DECC, 2009g)

As a result of the changes in fuel prices, various future price scenarios will be adopted in the sensitivity analysis of the financial appraisal. For the default financial appraisal

³⁴ These prices can be found on the website of those suppliers surveyed randomly, being; EDF Energy, N-Power, Scottish Power, and E.ON.

³⁵ Oil price quotes; <http://www.boilerjuice.com/> (assessed Thursday, 06 August 2009).

however, the current prices (as of August 2009) quoted above will be assumed constant in real terms over the lifetime of the microgenerators.

6.3 Default financial appraisal results

The results of the financial appraisal are presented in Figure 6.2, where the NPV is shown in the left-hand side and the corresponding benefit-cost ratio on the right. The default discount rate used is 5%, in accordance with the specification set out in Chapter 2.4.1.5.

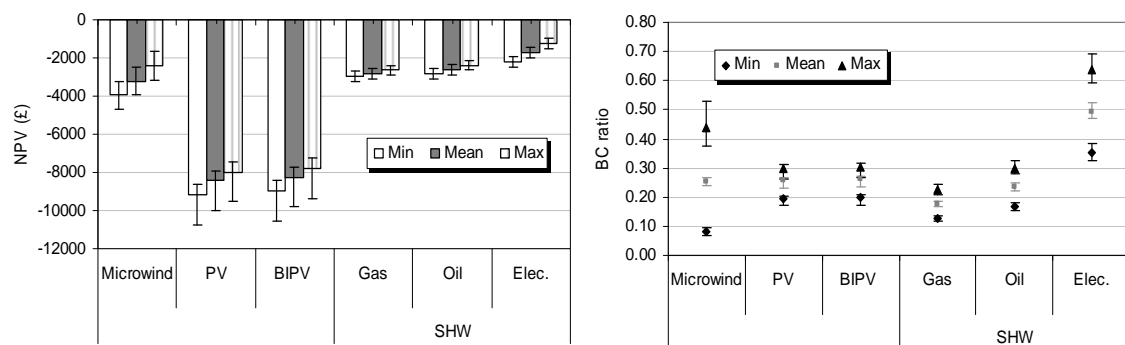


Figure 6-2 NPV and BC ratio for microgenerators; financial appraisal

The financial expected returns on the assessed microgenerators are highly unfavourable. The benefit-cost ratio for the solar PV/BIPV ranges from 0.19 – 0.32, i.e., for every £1 spent a return of 19 – 32 pence should be expected only. The BC ratio for the SHW system displacing natural gas ranges from 0.13 – 0.23, and SHW displacing oil ranges from 0.18 – 0.32 depending on the energy output and current capital cost assumptions. For SHW displacing electricity, the BC ratio is between 0.35-0.64 (depending on capital costs) for the mean energy output case, and 0.65 for the best case scenario. Figure 6.3 shows the simple payback periods for each microgenerator.

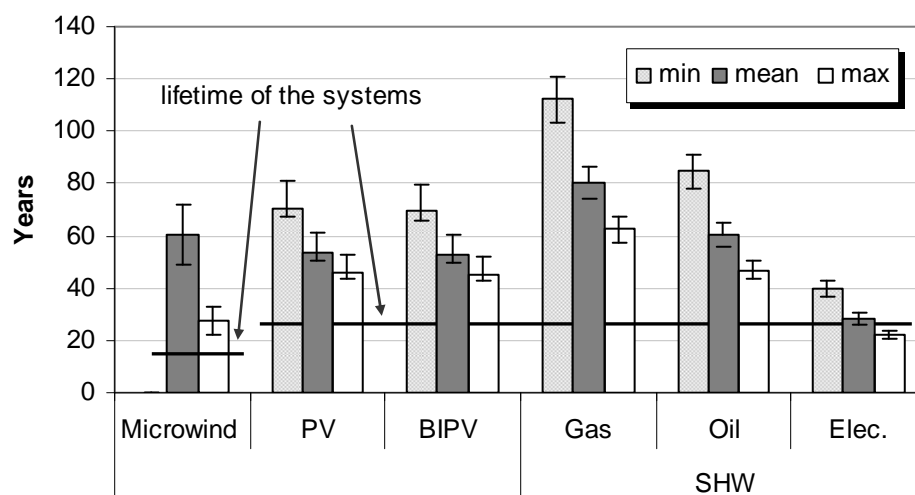


Figure 6-3 Simple payback period of microgenerators

Microwind fails to payback within its lifetime given the minimum (low) energy yield (therefore no bar is shown for the minimum energy output for microwind), while all the other microgenerators under different energy output regimes fail also to payback within their lifetime, with the exception of SHW displacing electricity under the maximum output case.

6.3.1 Default financial sensitivity analysis

The default financial appraisal has shown the unfavourable financial performance of the assessed microgenerators under all the possible energy output ranges and capital cost differences currently characterizing these systems in the UK market. Two other possible parameters may impact the financial results; the discount rate and the future possible price for fuel and electricity. Capital cost reductions have the potential to influence the results most, yet these will not affect the amount of investment required for purchasing a microgenerator today.

Changing the discount rate to take into account a ‘more patient’ individual, i.e., a 3% rate, or to assume a ‘less patient’ one, i.e., an 8% rate, did not have any major implications on the economics of the microgenerators. The 3% discount rate slightly improved the financial performances of the microgenerators, yet not nearly enough to change any significant conclusion about the systems. An 8% discount rate will further downgrade the financial results and deter any investment in the microgenerators.

Changes in the price of fuel and electricity could have significant implications for the microgenerators, specifically as their lifetimes extend significantly into the future. Electricity and fuel prices paid by UK residential customers are prone to fluctuations and this would be expected over the 15-25 year lifetimes of the systems. Figure 6.1 has shown a general increasing trend for fuel/electricity prices, something that the manufacturers of the assessed microgenerators in this thesis believe must be the default scenario. In the most recent ‘Updated Energy Projections’ (DECC, 2008b), four projections were proposed for oil, gas and electricity price projections were proposed up to the year 2025; ‘central fossil fuel prices’, ‘high fossil fuel prices’, ‘high-high fossil fuel prices’, and ‘low fossil fuel prices’. These assumptions are shown in Table 6.2.

Year	Electricity (p/kWh)				Natural gas (p/kWh)			
	Central	High	High-high	Low	Central	High	High-high	Low
2010	12.9	14.5	16.3	11	3	3.4	3.9	2.4
2015	12.3	13.9	17.9	10.7	3	3.5	4.8	2.5
2020	12.5	14.3	18	11.1	3.1	3.6	4.8	2.7
2025	12.7	14.7	18	11.2	3.2	3.7	4.8	2.7

Year	Oil (\$/bbl)				Oil (assumed p/kWh)			
	Central	High	High-high	Low	Central	High	High-high	Low
2010	65	85	107	45	4.5	5.8	7.2	3.2
2015	68	90	150	45	4.7	6.1	10.2	3.2
2020	70	98	150	45	4.9	6.7	10.2	3.2
2025	73	100	150	45	5.1	6.8	10.2	3.2

Table 6.2 Assumed electricity and fuel price (2010 – 2025)
(Source: DECC, 2008b)

The four possible future scenarios capture the more likely outcome range, which is considerable given the difficulty, if not impossibility of forecasting future energy prices. All price projections are assumed up to the year 2025. Therefore a further assumption will be to hold the projected 2025 prices constant for each energy courier up to 2034 – the end of the assumed lifetime of the PV/BIPV and SHW microgenerators. The projections of oil have been given in \$/bbl (i.e., US dollar per blue barrel of oil), therefore the percentage increase in these values were assumed also on the central oil price assumption adopted in the default financial appraisal (equal to 4.5 p/kWh).

The ‘central fossil fuel price’ scenario adopts almost constant electricity, oil and natural gas prices, and these values resemble those used by the default financial appraisal. In contrast, the ‘low fossil fuel price scenario’ anticipates 1-2 p/kWh decrease in the price for electricity, a 0.3 – 0.6 p/kWh reduction in the price of natural gas, and a reduction of about 1.3 p/kWh for the case of oil. Adopting these values from the ‘low fossil fuel price’ scenario will only dampen (slightly) further the financial appraisal results. Therefore, only in the possible future ‘high’ and ‘high-high’ fossil fuel price scenarios may some visible change to the financial appraisal results ensue. Results for the ‘high fossil fuel price’ scenario are expressed in terms of NPV and BC ratio in Figure 6.4.

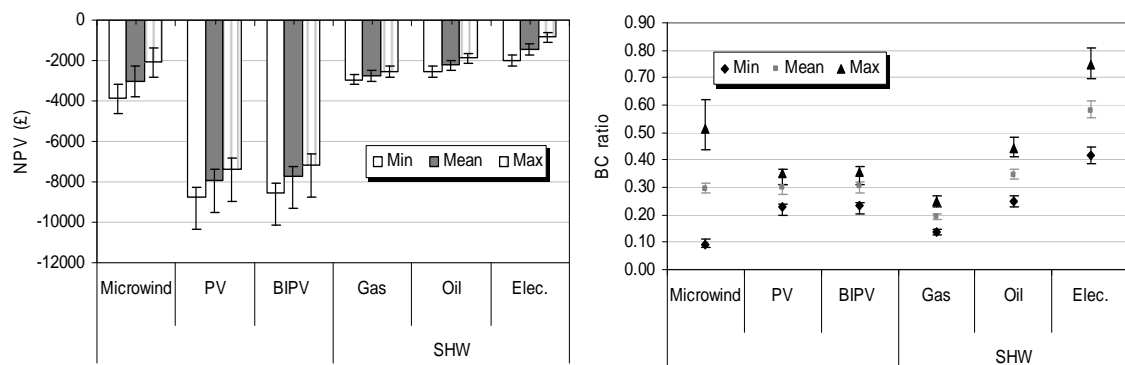


Figure 6-4 NPV and BC ratio for the microgenerators under the ‘high fossil fuel price’ scenario – financial appraisal

Comparing Figure 6.4 above with Figure 6.2, it can be seen that all the results have, as expected, improved slightly under the ‘high’ price scenario. However, none of the results shown in Figure 6.4 indicate a positive outcome where NPV is greater than or equal to zero or BC ratio is equal to or greater than 1.

The analysis is slightly better with the ‘high-high fossil price’ scenario as shown in Figure 6.5. The SHW system displacing maximum electricity with minimum capital costs will just about experience a BC ratio of 1, while the PV/BIPV will achieve BC ratios of 0.42-0.45 under the best case of energy and capital costs, and microwind will achieve a BC ratio of 0.6-0.7 in its best energy output case with mean and minimum capital costs.

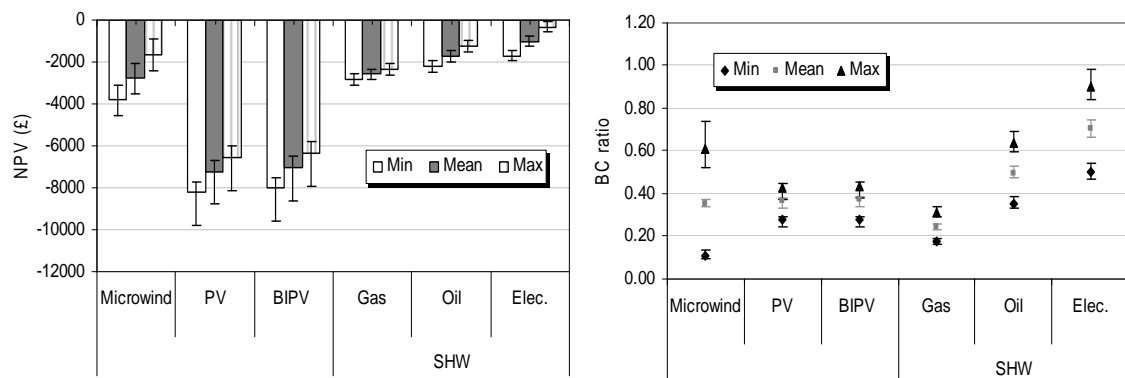


Figure 6-5 NPV and BC ratio for the microgenerators under the ‘high-high fossil fuel price’ scenario – financial appraisal

Given the undesirable financial returns of the microgenerators, which were not sufficiently improved by possible alternative future energy prices, support mechanisms are needed in the short to medium term if the objective of the UK government and civil society is to increase the deployment of these systems in order

to assist in meeting the dual challenge of reducing GHG emissions while ensuring a certain level of energy supply security. These issues are addressed in Chapter 8, particularly as the economic rationale of supporting the assessed microgenerators cannot be analysed in isolation, yet would have to be compared to other energy sources which deliver either electricity or heat (and hot water).

Several existing and proposed support mechanisms for microgeneration exist today in the UK, which will assist in their overall financial performances. These mechanisms and their impacts on the finances of the microgenerators are analysed shortly.

6.3.2 Microwind revisited

As done in the CBA, microwind is revisited for a better representation of the UK microwind market, correcting for both microwind scale (and consequently outputs) and capital costs. The capital cost range adopted (£1,785 - £2100 with a mean of £1945) includes the 5% VAT rate. Figure 6.6 illustrates the new NPV results using a default 5% discount rate.

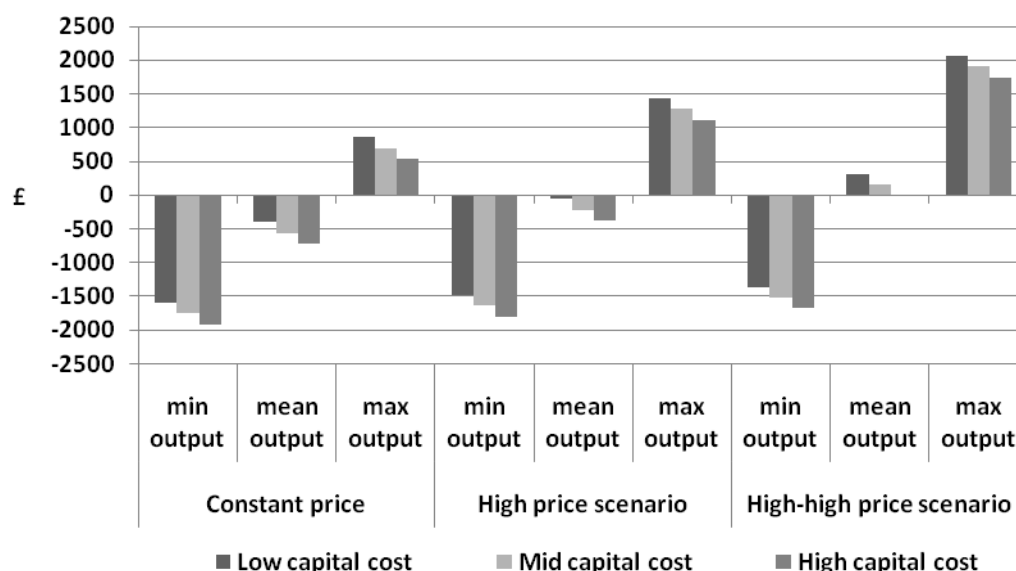


Figure 6-6 NPV of microwind; a more accurate UK representation

Figure 6.6 indicates a positive NPV for the financial appraisal of a microwind system under high energy output for all future price predictions, and under every capital cost range. The microwind system falls short of exceeding a zero NPV for the mean energy output condition with constant or high-price scenarios. Evidently, the output of the financial appraisal with more accurate representation of the UK market improves the situation considerably.

6.4 Government support mechanisms and their financial implications

The UK is currently (as of August 2009) in an important transitional period between two regimes or policies of government-led support for renewable energy technologies. The first regime involved (and still involves) a lax combination of subsidies, electricity export rewards, and renewable generation reward similarly applied to most renewable generation types and sizes. The newly proposed support scheme is based on differentiating between renewable energy types and sizes, and offering different mechanisms and support levels for each. Chapter 6.4.1 will review the current support mechanisms in place, and their impacts on the profitability of the three assessed microgenerators in the preceding section, while Chapter 6.4.2 will do the same yet for the newly proposed support mechanisms.

6.4.1 Existing support mechanisms and their financial implications

Financial support mechanisms currently available for the assessed microgenerators seem to balance between upfront capital-cost subsidies, exported electricity rewards, and rewards for overall total generation.

The current upfront subsidy support mechanism is known as the Low Carbon Buildings Program (LCBP). Grants are available for several microgeneration technologies subject to some necessary energy efficiency measures and planning consent criteria (DECC, 2009d). Table 6.3 elicits the available amount of subsidy for the three assessed microgenerators under the LCBP grant.

Technology	Maximum amount of grant	Assumed grant for assessed systems
PV	Maximum of £2,000 per kW of installed capacity, subject to an overall maximum of £2,500 or 50% of the relevant eligible costs, whichever is the lower	£2,500
Microwind	Maximum of £1,000 per kW of installed capacity, subject to an overall maximum of £2,500 or 30% of the relevant eligible costs, whichever is the lower	£600 (given that the assessed system is 600W)
SHW	Overall maximum of £400 or 30% of the relevant eligible costs, whichever is the lower	£400

Table 6.3 **Eligible LCBP grants for the three assessed microgenerators**
(Source; www.lowcarbonbuildings.org.uk)

So far only around 2024 PV systems, 6035 SHW systems, and 700 microwind systems have been committed by the LCBP grant, amounting to a total committed amount by the UK government of approximately £11.3 million (DECC, 2009d). The LCBP has been extended to April 2011, after which its continuation is subject to the overall outcome from the consultations on renewable electricity and heat financial incentives. For the moment, the three assessed microgenerators may obtain grants ranging from £400 to £2,500, as shown in Table 6.3.

For the electricity generating systems, a further reward can be obtained through the export electricity tariffs and the Renewables Obligation (RO) scheme. The ‘Climate Change and Sustainability Act’ (CCSA) adopted in 2006 ‘obliges energy suppliers to develop a scheme for export rewards for microgenerators otherwise the government

can impose a scheme' (Sauter, 2008). Specifically, the CCSA grants the government the power to take steps to increase the amount of electricity generated from microgenerators by requiring energy suppliers to make offers to acquire exported electricity generated from their customers. However no indication as to the level of the offer is specified (OFGEM, 2008). Subsequently, electricity export tariff rewards offered to microgenerators varied considerably between energy suppliers, and this was further complicated by the interfusion of the export rewards with renewable obligation certificates (ROCs). A ROC is a green certificate issued for eligible renewable sourced electricity generated in the UK and supplied to customers (OFGEM, 2009a). The Renewables Obligation sets a level for electricity suppliers to source at least part of their electricity from renewable generators. This level began in 2003 at 3% of electricity supplied, and is currently up to 9.1% for 2008-2009, and is expected to reach 9.7% by 2009-2010. The 'buy-out' price of the ROC is set yearly by the Office for Gas and Electricity Markets (OFGEM), yet will be set in the near future by the Department of Energy and Climate Change (OFGEM, 2009b). It is currently set at £35.76 for every 1 ROC, yet may increase, as it has since its inception (where it began at £30 per ROC), in order to encourage the uptake of renewable energy into the future and induce the market to meet the set renewable portfolio target.

The amount of ROCs issued for each MWh generated depends on a combination of factors such as the technology used, the location of the generating plant, the installed capacity of the generator, and so forth. For most stations with a total installed capacity of 50kW or less (i.e., under the umbrella of microgeneration), the number of ROCs issued per MWh is 2 – rounded to the nearest whole ROC for the purpose of certificate issuance (OFGEM, 2009a). This is a new banding amendment to the RO which came into force in April 2009 and delivered different ROCs to different technologies. Before this amendment, 1 MWh was equal to 1 ROC across all technologies.

Furthermore, microgeneration was exempted from 'grandfathering', meaning the microgenerator will be able to attract the value of the ROC as set in each year, as opposed to being paid the value of the ROC as set on the first year of the microgenerator's operation. In other words, microgenerators are exempt from 'grandfathering' (OFGEM, 2009a).

The CCSA therefore left a lot of decisions to be taken in the electricity market, and consequently many financial offers are available that UK energy suppliers provide households that have microgenerators installed. Some of these offers combine the ROC with the export rewards, others separate the two, yet most (except one energy supplier) require that the exporter be also an importer from the same company. This last condition complicates the calculation of the profitability of the offer at hand. This means that it will be the net result from import tariff levels, export tariff levels and how the ROCs are shared between the microgeneration-source householders and their respective energy suppliers that will determine the overall financial performance of the microgenerator.

The suppliers of microgeneration electricity will prefer to attract the same price for their exported electricity as they are charged for their imports, in other words they would like to acquire the retail electricity price as opposed to the wholesale electricity price (OFGEM, 2008). The retail price could be considered twice that of the

wholesale price, due to additional costs associated with supply costs and generation margin, transmission use of system (TUoS) and distribution use of system (DUoS) charges, metering, and paying for the carbon reduction certificate charges³⁶ and the RO itself (OFGEM, 2008). The value of microgeneration to energy suppliers on the hand is difficult to determine, primarily due to; (1) the wholesale energy costs fluctuating constantly in response to demand, primary energy costs, and capacity margins, (2) due to the unpredictability of the time the microgenerators will be exporting – let alone generating, and (3) the difficulty in knowing the exact upfront and on-going transaction costs suppliers are subjected to in signing up microgeneration customers (OFGEM, 2008). In addition, the relatively small amount of electricity per household exported from a microgenerator makes it less appealing to an energy supplier (DECC, 2009c). OFGEM (2008) indicates that the benefits of microgeneration to an energy supplier should be the wholesale value of electricity plus the avoided distribution and transmission charges, in addition to the avoided TUoS, while the costs involved are due to the costs to enable export (such as a meter for example) and additional meter readings per year. The net benefit will range from 0.1 p/kWh to around 6 p/kWh (OFGEM, 2008).

A further categorization of the offers provided by energy suppliers to their customers can be divided by whether the customers have metered offers, unmetered offers, or generation based offers (OFGEM, 2008). The metered offer pays for the exported amount of electricity which would be monitored and known, while the unmetered offers make a fixed annual payment regardless of how much is exported (calculated after the specific characteristics of the customer and level of generation). Finally, while generation offers are based on the ROC value of the total amount generated regardless of how much of that was exported. To simplify the analysis, and given the commitment of the UK government's intention to roll out smart meters in every UK household by 2020 (Reuters, 2009), Table 6.4 shows several reward schemes offered by UK energy suppliers (as of August 2009) for metered schemes only.

#	Energy Supplier	Reward (p/kWh)		ROC	Import price (p/kWh)
		Exports	All generation		
1	British gas	5	-	Customer claims ROC separately	11.5
2	E.on	9 – 11.2	-	Customer claims ROC separately	10
3	EDF	7.64	-	Customer claims ROC or Supplier is ROC agent	10.9
4	Ecotricity	-	12	Supplier is ROC agent	12.4
5	Good Energy	-	15	Supplier is ROC agent	13.5
6	NPower	10 (microwind) 12 (PV)	-	Supplier is ROC agent	12.9

³⁶ Under CERT, energy suppliers must, by 2011, deliver measures that will provide overall lifetime carbon dioxide savings of 154 MtCO₂ – equivalent to the emissions from 700,000 homes each year. It is expected to lead to energy supplier investment of some £2.8bn (DEFRA; <http://www.defra.gov.uk/environment/climatechange/uk/household/supplier/cert.htm>)

7	Scottish & Southern Energy	A) 5 B) 28 for PV only	-	A) Supplier will also pay £46 per ROC if appointed as customer's ROC agent. B) ROC is inclusive of 28 p/kWh export reward	12
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Table 6.4 Financial export rewards and ROCs as listed for several UK energy suppliers
(Source: EST, 2009)

Table 6.4 shows that the eventual financial returns of a microgenerator will be dependent on the energy supplier selected. In certain situations, only the export electricity is rewarded and the ROC value is given to the customer to deal with and obtain independently, in others all generation is rewarded but that reward value includes the benefits of the ROCs which the energy supplier will take for its own.

Information about the export quantity percentage of each assessed microgenerator, specifically in this case the PV/BIPV and the microwind systems, is required in order to estimate the total benefits of the offers indicated in Table 6.4. For microwind, Peacock *et al.* (2008) indicates that export percentages are significantly influenced by the turbine size, where a 2.5 kW turbine exports between 52% and 71% of electricity generated while 0.6 kW - 1.5 kW turbines export between 48% and 63% respectively (Peacock *et al.*, 2008). For PV/BIPV systems on the other hand, Bahaj *et al.* (2007) monitored nine low-energy social housing units equipped with PV systems commissioned in 2004 in the South of England, UK. Most of the houses monitored exported between 40% – 70% of their electricity, with one house exporting 25% only (Bahaj *et al.*, 2007b). These export percentages fall within the percentages assumed by the EST *et al.* (2005) which indicated 50% and 60% export from PV and microwind respectively (EST *et al.*, 2005). These later figures will be assumed in this analysis.

Given the export percentages, and the offers on display from Table 6.4 – including the respective import price, Figure 6.7 presents the annual benefits expected from exported rewards and the ROC together, along with the remaining import prices, and the net annual benefits as applied by the 7 energy suppliers.

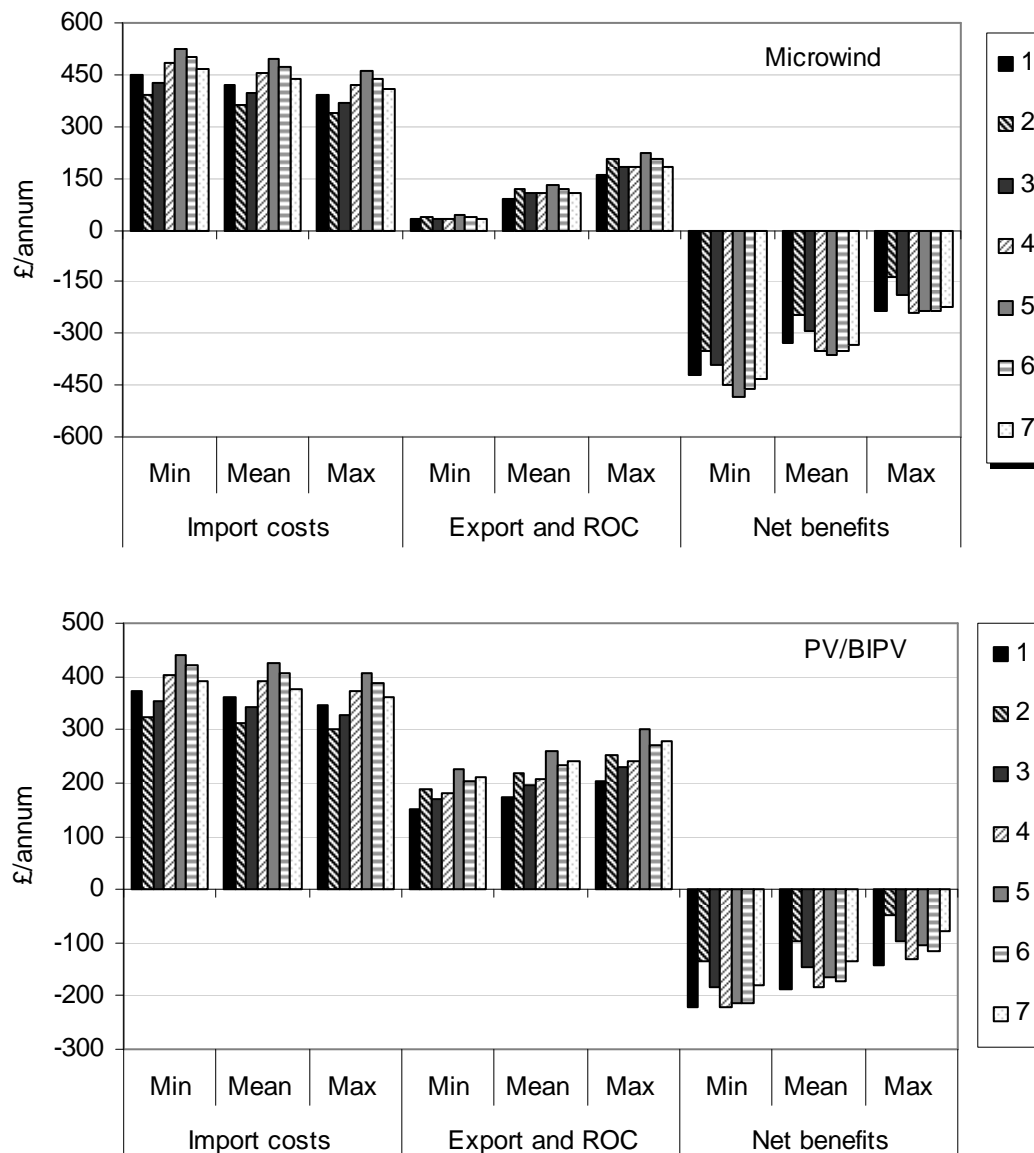


Figure 6-7 Annual import costs, reward benefits, and net benefits of 8 UK energy suppliers

Figure 6.7 shows that there could be some significant differences between energy suppliers in terms of their import prices and reward scheme levels for microgeneration, including the ROCs. The minimum benefits (i.e., export benefits and ROCs) accrued goes to energy supplier 1 (i.e., British Gas), while the best benefits goes to energy supplier 5 (i.e., Good Energy). However, supplier 2 (or E.on) ends up with the best scheme overall after import costs are accounted for, assuming an average household consumption of 4,000 kWh and the assumed export percentages of microgenerator output. As supplier 2 separates the export rewards from the ROCs, and achieves a maximized net benefit, the financial appraisal will assume that export reward for assessed PV/BIPV and microwind system's electricity will be equivalent to 10 p/kWh, while they will be able to attract ROCs on all their generation as well.

With respect to solar hot water, the UK government is scheduled to put forward by April 2011 a Renewable Heat Incentive (RHI) following consultations. Therefore for the current time, only the LCBP grant outlined above is currently applicable to the SHW system.

The total net benefits from the installation of the PV/BIPV and the microwind systems can be given by the following equation;

$$NPV = \frac{(\text{Displaced imports worth} + \text{export worth} + \text{ROC worth}) - (\text{Total costs})}{(1 + r)^t} \quad 6-1$$

The financial appraisal of the microgenerators with the available current government-led support outlined above achieves considerably better results than those obtained from the default appraisal. These results are shown in Figures 6.8 and 6.9.

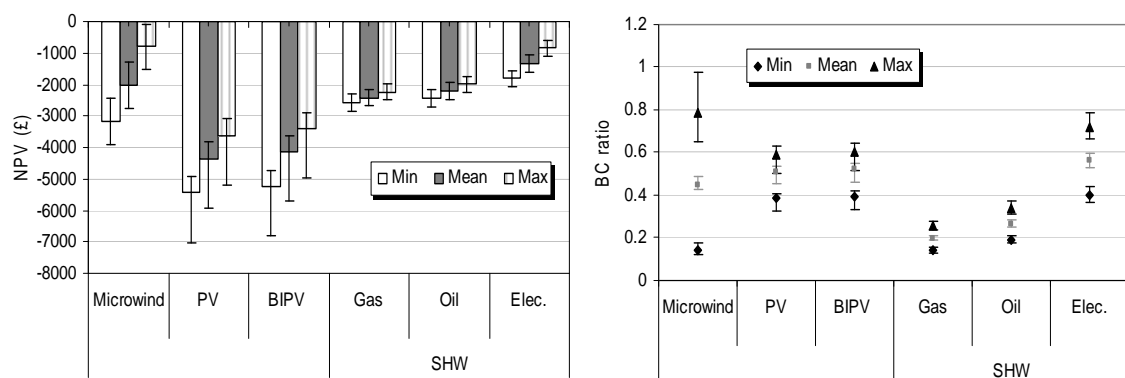


Figure 6-8 NPV and BC ratio of microgenerators with export support, ROCs and the LCBP grant

In Figure 6.8, microwind almost breaks even under the low capital – high output case, having a NPV of -£70 and a BC ratio of 0.97. All other microgenerators improve their performance, with SHW displacing electricity improving its BC ratio to 0.8 for example. No technology does enough to achieve a NPV of at least 0 or a corresponding BC ratio of at least 1.

Within the simple payback method shown in Figure 6.9, microwind pays back within its lifetime under the high wind – low capital costs, as do the PV/BIPV and SHW displacing electricity systems.

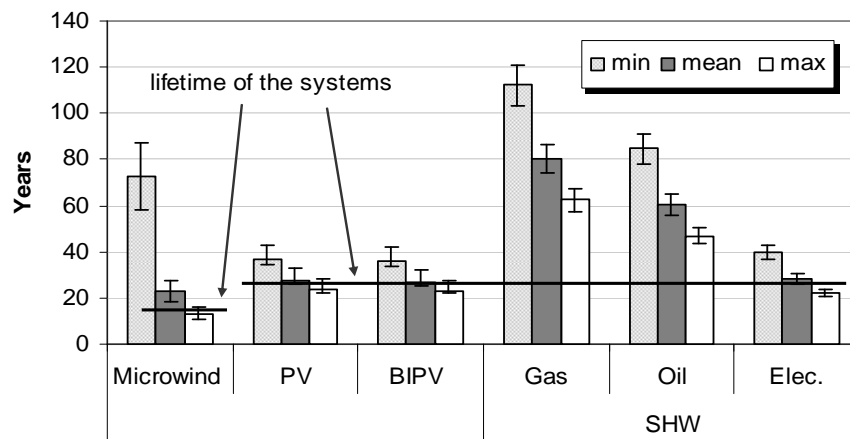


Figure 6-9 Payback (years) of microgenerators with export support, ROCs and the LCBP grant

Undoubtedly, possible future increases in electricity or fuel prices – such as the ‘high’ or the ‘high-high’ energy scenario, will improve the overall financial performance of the systems, and would change the export reward gained. However, no such scenarios will be modelled here, as the entire support mechanism for microgeneration are bound to change, particularly after the current consultation on Renewable Electricity Financial Incentives (2009) and the Renewable Heat Initiative (RHI) consultations are completed and approved into Laws or Decrees in the UK. The next section covers the potential financial implications on the microgenerators if the newly proposed support mechanisms are put to place by the Department of Energy and Climate Change.

6.4.2 Proposed support mechanisms and their financial implications

New support mechanisms are being currently developed for all types of renewable energy sources; for heat and for electricity. The UK Renewable Energy Strategy (BERR, 2008b) hinted at the possibility of separating support mechanisms between those targeting large scale renewables and those for microgeneration, paving the way for feed-in tariffs (FITs) for the latter while leaving the Renewables Obligation for larger scale systems. Similarly, new schemes for heat that do not rely solely on grants like those currently delivered by the LCBP mentioned above were pointed out and consultations on them are in process. These schemes involve the RHI which is like a FITs for heat, and the Renewable Heat Obligation (RHO), which is like the RO for electricity also (BERR, 2008b). These expected financial instruments may either replace the current LCBP grant or compliment it, the latter specifically being more beneficial for heating technologies. No published values for the RHI or the RHO have been set yet; therefore the analysis of Chapter 6.4.1 with respect to the SHW system remains as is. For the BIPV/PV and the microwind systems however, a new FIT mechanism and value levels have been recommended in the Consultation on Renewable Electricity Financial Incentives (DECC, 2009c). As it stands, the FITs would replace completely the LCBP grant and other support mechanisms for microgeneration, unless changes occur through the responses on the Consultation expected by October 2009. Therefore, this section will briefly describe the key elements behind the newly proposed FIT system for microgeneration, and use its key

assumptions and values to find out whether or not this scheme will enable the PV/BIPV and the microwind systems to break even within their lifetime.

The Energy Act 2008 provided the ground-works for the introduction of the FITs for small scale low carbon electricity generation that do not exceed 5MW in capacity (DECC, 2009c). FITs are per unit support payments for electricity generation and are the primary vehicles for supporting small-scale renewables in the Europe.

The proposed FIT structure is as follows (DECC, 2009c);

- A fixed payment from the electricity supplier for every kilowatt hour (kWh) generated (the “generation tariff”).
- Another payment additional to the generation tariff for every kWh exported to the wider energy market (the “export tariff”). Generators will be guaranteed a market for their exports at a long-term guaranteed price. The generator may choose whether to sell exported electricity to the supplier at this guaranteed export tariff, or negotiate a price for exported electricity in the open market.

The FIT system includes all the electricity generated in order to prevent the householder from exporting all the electricity provided by the microgenerator, thereby encouraging some of the additional benefits of microgeneration such as avoided network losses from consuming electricity on-site. The generating tariff would be a fixed price (p/kWh), set at different levels for different technologies and installation sizes and paid for a proposed period of 20 years for all microgenerators with the exception of PV/BIPV that will have FITs for a proposed 25 year period (DECC, 2009c). The FIT would be subject to ‘degression’ to follow through the expected capital cost reductions (see Chapter 7), meaning that tariffs for new projects would be reduced annually to reflect (and encourage) expected decreases in technology costs (DECC, 2009c). However, the tariffs paid for microgenerator output will be ‘grandfathered’, meaning that they will remain the same of the proposed 20-25 year period.

Concerning exported electricity, it has been shown that the unpredictability and the small amount of electricity produced by the microgenerators make their value to energy supplier significantly lower than the retail price of electricity. According to DECC (2009c), there is evidence that uncertainty around the value of returns from a microgenerator results in them being heavily discounted by financiers, therefore an ‘export tariff’ is proposed in order to maintain long-term certainty for exports through obliging energy suppliers to purchase exports at a guaranteed minimum price. This price should be, according to DECC (2009c), set between the ‘spill price’ – which is the minimum price paid for unplanned exports, and the retail price. Although no definite value has been given, a 5 p/kWh has been suggested (DECC, 2009c).

Table 6.5 lists the proposed tariffs for the assessed microgenerators, along with the annual degression percentage that is to reflect the expected capital cost reductions of the technologies.

	System	Comment	Proposed initial FIT (p/kWh)	Annual depression
1	PV < 4 kW (new build)	Assumed for BIPV only	31.0	7%
2	PV < 4 kW (retrofit)	For PV only	36.5	7%
3	Microwind < 1.5 kW	-	30.5	4%

Table 6.5 Generation feed-in tariff (FIT) for first year only (2010-2011)
(Source: DECC, 2009c)

The proposed FITs presented in Table 6.5 appear rather substantial, amounting to 36.5 p/kWh for the PV system and 30.5 – 31 p/kWh for microwind and BIPV systems, respectively. Figure 6.10 illustrates the financial appraisal results of the BIPV/PV and microwind systems under the newly proposed FITs.

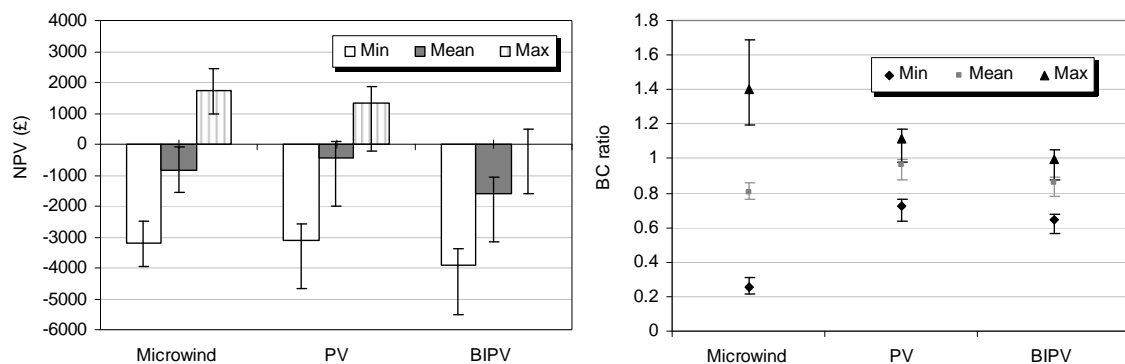


Figure 6-10 NPV and BC ratio of microgenerators under the proposed FITs

Under the maximum output scenarios, microwind achieves a NPV of £1,732 with the mean capital case, with a corresponding BC ratio of 1.4. The best case for microwind provides a BC ratio of 1.69. For PV, the NPV and BC ratio exceed 0 and 1 respectively under the minimum and mean capital cost with maximum output scenarios. The mean output and capital cost scenario for PV just falls short (BC ratio equal to 0.96) however with the new FIT scheme. BIPV will see improved financial performance with the FIT regime, achieving a BC ratio of 1 and above under its maximum output condition with mean and low capital costs. It falls slightly short under the mean output condition.

Figure 6.11 illustrates that all the systems under most of the cases will payback their investment with the proposed FIT regime with the exception of microwind under its low energy yield scenario. The simple payback method will indicate a different picture than the NPV and the BC ratio indicators given the absence of time valuation or discounting.

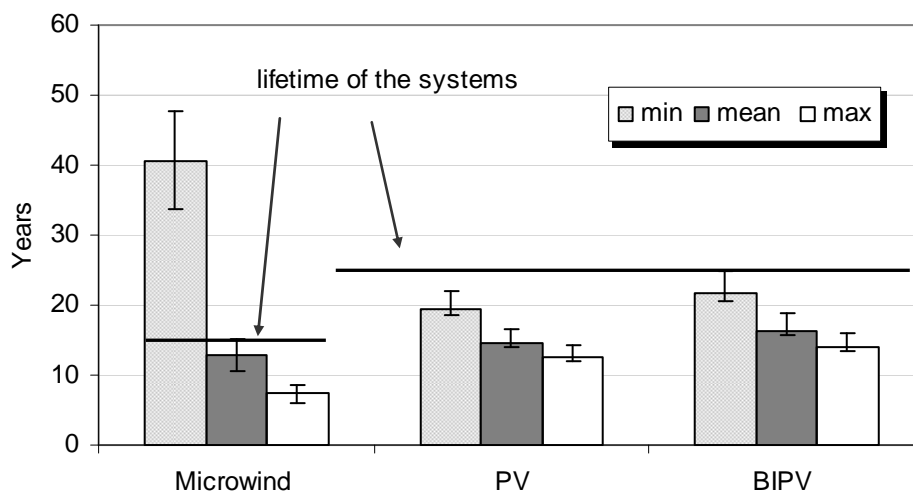


Figure 6-11 Payback (years) of microgenerators under the proposed FITs

The proposed FIT structure and levels for the UK would enable the assessed electricity-supplying microgenerators to break-even within their lifetime. This was not possible with the Renewables Obligation (RO), even after banding the RO so that 1 MWh of power produced from the microgenerators would be worth 2 ROCs instead of 1, in addition to the LCBP grant. The RO is a kind of renewable portfolio standard (RPS) model which leaves the decision as to which technology to select to energy suppliers. They, in turn, would most likely select the cheapest way of obtaining a ROC, inducing them to select more mature or well-established technologies. In the UK, this has led to investments in large onshore wind farms, and land-fill gas and energy from waste projects, yet has not led to any major impacts on microgeneration levels (Lipp, 2007). Furthermore, the RO lends support to economies-of-scale, pushing energy suppliers to meet their RO through large energy projects, while the administrative hassle of obtaining 1 ROC from a domestic householder may outweigh the benefits of obtaining ROCs in this manner.

The LCBP grant assisted in lowering the capital costs of the microgenerators, however they were used up fairly quickly, and only induced the installation of around 2024 PV, 6035 SHW, and 700 microwind systems, as mentioned earlier, amounting to a total committed amount by the UK government of approximately £11.3 million only (DECC, 2009d). This amount is far from being sufficient to encourage the deployment of the above microgenerators, if the latter is the objective. Further discussion about the rationale for supporting the assessed microgenerators, particularly in context of other energy generating sources, is returned to in Chapter 8.

The proposed FIT model has the potential to spur the microgeneration market in the UK, given that it has successfully done so in other European nations like Germany and Spain. The FIT system would consolidate the objective of bringing stability and security for investors in this field over long periods of time (20-25 years). National FITs “*create harmonization, consistency, and predictability for financiers, investors, manufacturers, and producers... and helps manufacturers and industry by providing a consistent and predictable statutory environment*” (Sovacool, 2009). The FITs would

also have the added sensitivity to regard different technologies according to their respective different areas of development, therefore supporting more the relatively less mature technologies like PV, while at the same time encouraging cost reductions given the annual degression of the FIT levels.

Opponents of the FIT system argue that it is an expensive way to support RE development, given that consumers and taxpayers eventually pay for that support (Lipp, 2007). However, evidence from Germany and Spain, for example, have shown that while their FITs cost their respective consumers in higher electricity rates and administrative expenses about £3.3 billion and \$1 billion in 2007, respectively for each country, it has saved Germany around \$5 billion in depressed fossil fuel costs and \$9.4 in overall costs, and it has saved Spain \$1.7 billion in avoided costs (Sovacool, 2009).

Lipp (2007) has observed that the FITs were potentially one of the main reasons (among others like policy consistency) for the success of renewable energy deployment in Denmark and Germany, while the lack of such a policy has played a role in delaying the adequate deployment of renewables in the UK. Lipp (2007) argued that if the reasons for deploying renewable energy are (1) related to ensuring a more adequate security of supply (specifically reduced dependence on fuel imports and creating diversity of supply), (2) reducing GHG emissions, (3) fostering innovation and broadening industrial capabilities, and (4) increasing local and regional benefits through, for example, job creation, then Denmark and Germany have more successfully achieved these aims in comparison to the UK. It would therefore be interesting to observe the potential impacts of the proposed FIT system to be introduced to the UK in 2010, and whether it will induce the same amount of deployment of microgeneration as it has in other European nations.

6.5 Impacts on housing (property) values

In the first quarter of 2003, the EU Directive on the Energy Performance of Buildings came in force to improve energy performance of European buildings. Under article 7, energy performance certificates (EPCs) 'must be made available whenever a building is constructed, rented or sold' (EST, 2007). The EPC aims to encourage buyers and sellers to improve the energy efficiency and reduce the environmental impacts (CO₂) of their property in order to bring market differentiation on the basis of energy performance. An illustration of an EPC configuration is shown in Figure 6.12.

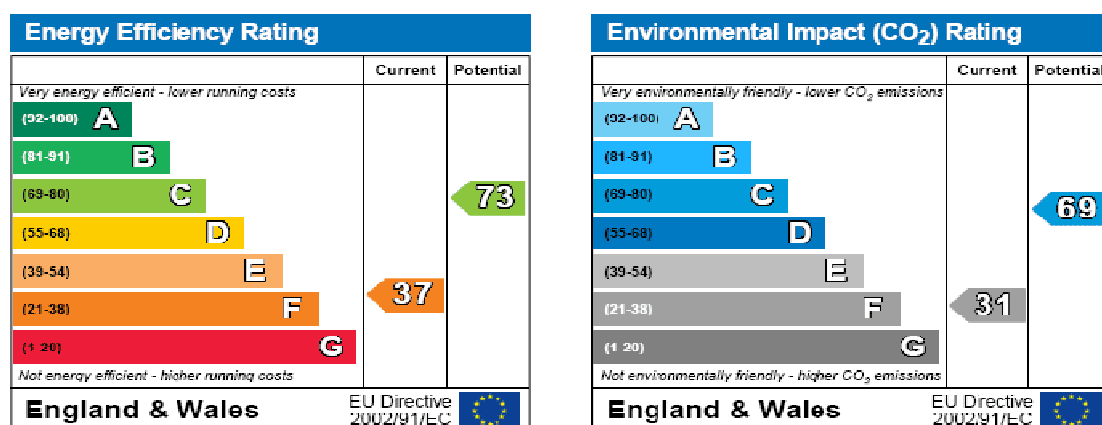


Figure 6-12 Energy Performance Certificates (EPCs)

Figure 6.12 provides an example of a domestic household EPC that carries ratings comparing the current energy efficiency and carbon dioxide emissions with potential figures that your home could achieve, the latter calculated by estimating what the energy efficiency and CO₂ emissions would be if particular energy saving measures were put in place. The rating measures the energy and carbon emission efficiency of your home using a grade from ‘A’ to ‘G’; where an ‘A’ rating is the most efficient, while ‘G’ is the least efficient (EST, 2008a). The EPC is currently required by law when a building is constructed, sold or put up for rent.

Within this EPC scheme, micro-generators could be included as further measures that would undoubtedly contribute positively to the energy and environmental impact rating of the examined household. This improvement in rating could be then directly (and potentially) translated into economic value and/or benefits given that the running expenses of the house would decrease. A similar situation will be the relatively enhanced value (price) of a more fuel efficient vehicle in comparison with a similar less efficient brand.

For example, a study by the American Solar Energy Society has indicated the following with respect to the impacts of solar PV on house value (Black, 2004b);

“Solar electric systems can reduce or eliminate the current and future energy operating cost of the home. They hedge against or eliminate the effect of electric rate inflation and in many cases can provide an attractive vehicle for financial investment. A solar electric system increases home value by \$20,000 for each \$1,000 in annual reduced operating costs due to the system”.

This statement has been further expanded on in Black (2004a). For the mean energy output of a PV system and the current retail rate of electricity, this 1:20 ratio claim would mean that installing a PV system should increase a UK household price by about £4,000. If the same reasoning is extended to SHW systems and microwind, a UK property value should increase by \$1,200 at least if the former is installed, while an increase of £2,000 should be expected from the latter.

However, the Energy Saving Trust (EST) has indicated that *“an energy efficient home will not only command higher rental value and boost chances of a property being rented, but can also increase the value by an average of £3,350 when it comes to*

being sold’ (EST, 2008a). The latter claim is a combination of energy efficiency and possible microgeneration measures as guided to by the EPC, indicating consequently that the 1:20 ratio claim for a PV system alone seems to be an overestimation of the benefits. How much the values of properties are impacted by microgeneration alone will therefore need further research, perhaps through hedonic pricing method studies (see Appendix 2).

Nevertheless, it is certain that the assessed microgenerators will contribute favourably to the EPCs, and that the higher the score on those certificates achieved by a household the more likely the property will appreciate in value. Whether or not an individual will gain financially from this appreciation would only be realised if and when the property is sold (or rented).

6.6 Discussion; Linking FA to CBA

The financial appraisal applied on the selected microgenerators was divided into three parts. The first part, the default FA, has revealed that all the assessed systems, on an individual household or incentive level, fail to return the investments they require. Under the best condition of maximum energy output combined with minimum capital costs, keeping the price of energy constant in real terms, a household can expect 42 pence back on a £1 investment for microwind, and only 38, 39, 26, 54, and 76 pence back on a £1 investment for PV, BIPV, and SHW displacing natural gas, or oil, or electricity, respectively. These are improved if the ‘high-high’ fossil fuel price scenario occurs in the future, and expected return would amount to 74, 44, and 45 pence on a £1 investment for microwind, PV, and BIPV, respectively, and 34, 69, and 98 pence return for SHW displacing natural gas, or oil, or electricity, respectively. These returns clearly indicate the need for these systems of government-led support.

Initially and currently, the LCBP up-front grants and the ROCs improved the economics of these systems considerably. It was shown that a £1 investment, with the LCBP grant, almost enabled a £1 return for microwind in the best case energy output-capital cost combination. The grants however fell short in enabling other technology to return their respective investments sums, even under their best case energy-capital cost combinations.

The proposed financial mechanisms, specifically the FITs, are more ambitious in their support levels for the electricity-supplying microgenerators. Microwind and PV returned a £1 investment for a £1 investment under their respective mean energy output conditions with minimum capital costs, while BIPV returned 90 pence under the same conditions. The best case for all these three microgenerators yielded £1.7, £1.17, and £1.04 return on a £1 investment for microwind, PV, and BIPV, respectively, and also yielded a BC ratio of 1 or over for the mean capital cost cases under maximum output for these technologies. The systems only fell slightly short of a BC ratio of 1 under the mean capital cost and mean energy output scenarios. This level of support is expected to shift the gears on the uptake of these systems in the UK.

The three-part FA showed that even if the microgenerators yield other society-wide benefits in the CBA, such as reducing environmental emissions from centralised

electricity sources, on an individual level significant support is required to incentivise these systems to domestic household clients in order to realise those environmental benefits. In classical environmental economics, a market is considered efficient if the marginal social costs are equal to the marginal social benefits (see Figure 2.7). If the FITs are proposed mainly in order to support the microgenerators on environmental grounds, then in theory the level or amount of support given to these systems should not be more than the environmental benefits they each accrue, respectively. Figure 6.13 compares the two.

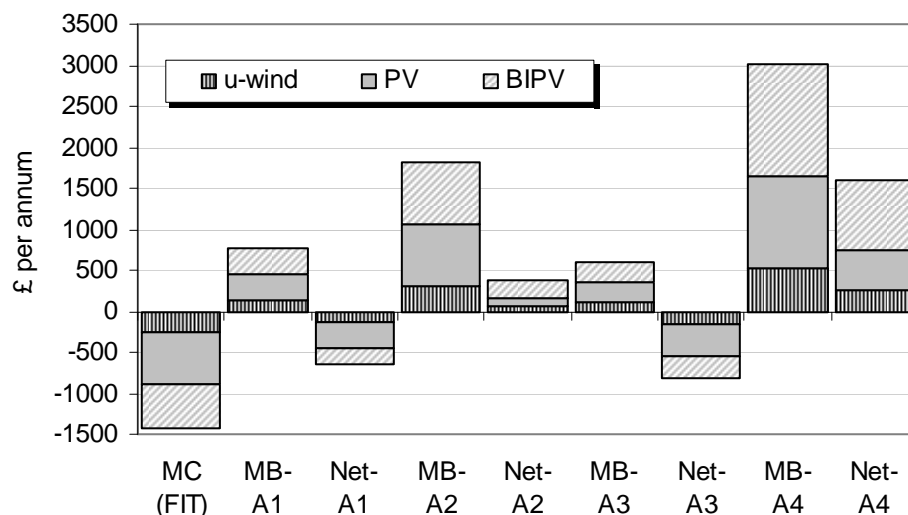


Figure 6-13 Annual cost (FITs generation tariff), annual environmental benefits under 4 alternative approaches, and net effect for 3 microgenerators

The four approaches of environmental quantification and monetization are reproduced here from the CBA. The mean energy output for each indicated microgenerator is used. Figure 6.13 indicates that adopting approaches 1 and 3 would not justify such costs incurred for the FITs, specifically the generation tariffs, given that the environmental benefits (MB-A1 and MB-A3) do not offset these costs (MC – FIT), shown by a negative Net A1 and negative Net A3.

However, adopted approaches 2 and 4 more than offset the cost of applying the FITs, lending justification for such support. Only the generation tariff is included, given that the ‘export tariff’ could be considered to cover the part of the value of electricity. This analysis does not consider other important attributes that the microgenerators may provide, which are discussed in Chapters 7 and 8.

7 Other CBA Considerations; Non-Monetized Attributes

Many important attributes that concern the assessed microgenerators have not been included in the CBA of Chapter 5, and therefore a qualitative assessment and the assessment of positive (learning) externality are merited as indicated in the decision tree of Figure 2.9 of Chapter 2.

These attributes are numerous and they include; (1) the future economic prospects of the microgenerators and the resulting implications on the CBA results outlined in Chapter 5, (2) the potential impacts on the actual total use of electricity induced by the electricity-generating microgenerators if accompanied by a smart meter, (3) the socio-economic and social implications of microgeneration, for instance, concerning issues such as the impacts of the microgenerators on employment, and possible psychological benefits for the installer of the systems, and (4) the possible consequences on the UK electricity network and security of supply.

Some of these attributes are monetized in this Chapter, however are not included in the original CBA of Chapter 5 given that either (1) they have not been monetized before (specifically the positive learning effects), or (2) that further research is required to validate them (specifically double-dividend effects). Other issues, such as psychological effects, could not be monetized, and would require alternative approaches in order to do so, such as through contingent valuation studies for example. These will be treated qualitatively and will be readdressed in Chapter 8 through a SMART.

7.1 Non-monetized attributes

Three non-monetized qualitative attributes are addressed in this section; employment benefits, local empowerment and self-reliance, and psychological implications.

7.1.1 Employment benefits

The renewable energy sector in the UK is passing through a transformational phase where it is attracting a lot of focus from the UK government and the general society at large, given the current worries about climate change (see Chapter 1) and energy security (see Section 7.3). In 2007/08, the world ‘low carbon and environmental goods and services’ (LCEGS) sector contributed approximately £3.047 trillion, 27% of which was attributed to Europe (BERR, 2009). In the UK and within the same year interval, there were approximately 881,000 people employed in the LCEGS sector alone (representing 3% of the current total employee base), of which 432,000 are in the emerging low carbon sector; 257,000 in the renewable energy sector; and 192,000 in the environmental sector (BERR, 2009). The PV industry accounts for approximately 38,007 employees in that year (BERR, 2009), while the microwind industry has currently about 2,585 direct and indirect jobs (2009), forecasted to reach 3,850 by 2010 given the strong export potential of microwind (BWEA, 2009). With respect to solar hot water, there are approximately 100,000 systems installed in the UK representing 0.4% of all UK households, and a growing rate of installations are occurring per year as can be deduced from Figure 7.1.

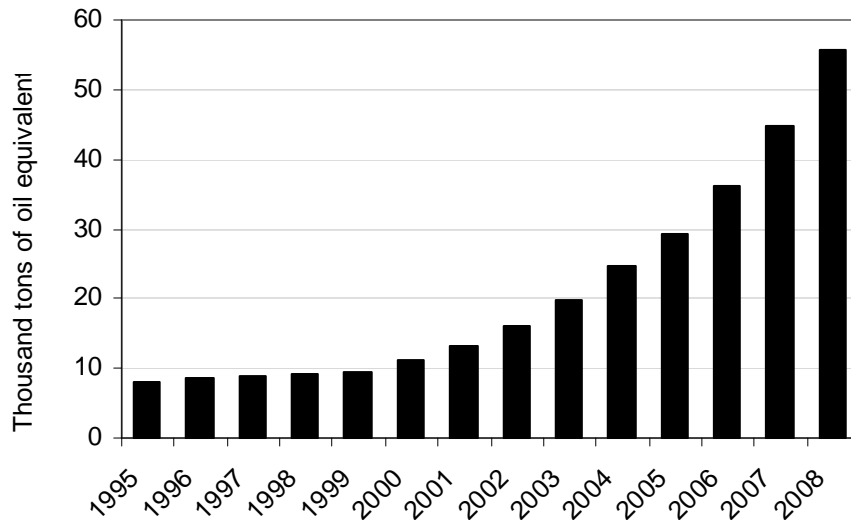


Figure 7-1 UK SHW system uptake
(Source: BIS, 2008)

Given that the UK Renewable Energy Strategy (DECC, 2009i) has committed the UK to a 12% share of heat to come from renewable sources, the expected increase in SHW systems annually should be no less than 40% from now up to 2020 according to a scenario adopted by Enviros for the BERR which corresponds to the Renewable Strategy's goal (Enviros, 2008). This would have substantial implications on employment in the SHW sector, the exact magnitude of which has not been referred to by the literature.

In general, the overall LCEGS employment sector is forecasted to grow at over 4.5% per year over the next eight years (BERR, 2009), which corresponds well for the forecast of microwind that 'by 2020 there will be 5,800 employed in the microwind sector' (BWEA, 2009). For PV however, the forecast is closer to 8% (BERR, 2009). These estimates were forecasted before the proposed feed-in tariffs (FITs) indicated earlier. The FIT will undoubtedly further speed the uptake of the PV and microwind systems.

A further benefit of microgeneration with respect to employment is that the created employment opportunities may also induce a slight level of economic restructuring. Lovins *et al.* (2002) indicate that 'many distributed resources lend themselves to local manufacturing using relatively widespread skills and nearly all can support local operation and maintenance activities...' In specific, Lovins *et al.* (2002) point to the fact that "*projects that use local or renewable inputs produce greater local economic benefits than those that haul fuel and other inputs from far away. This will create more local (host) community employment, secure more salaries and wages, and will be potentially viewed as a source of local re-spending, stimulus and prosperity*". Examples elsewhere lead to the same premises, for example, in New Zealand the local energy system could 'lead to the creation of local industries and to the up-skilling of electricians, plumbers, engineers, and others involved in the installation of local energy systems' (PCE, 2006).

Undoubtedly therefore, and particularly with current government support, renewable energy and microgeneration are offering an innovative and dynamic economic system

that is aimed first and foremost at restructuring the energy-related economic agents away from the traditional energy supply chain into the renewable chain with repercussions to local communities in terms of employment. These employment opportunities potentially would yield more returns to local enterprises and would therefore lend further support to the positive socio-economic implications from renewables in general and micro-generation in part. The exact magnitude of the expected employment benefits from microgeneration relative to other low-carbon investments, such as energy efficiency, will depend on the actual consequences of the new government support proposals (i.e., FITs) to be launched. Microgeneration has been suggested to have moderate implications on job opportunities when related to other green-stimulus' investments (Bowen *et al.*, 2009).

Nevertheless, it remains difficult to monetize the actual benefits of one PV, or microwind, or SHW system in terms of initiated increased employment. The overall impacts depend on the penetration levels of the microgenerators and therefore the impact of any one installation, although contributing to the whole, is minimal. Furthermore, the issue cannot be judged in isolation to what will occur in the job market as a whole. In other words, would the jobs created be displacing other jobs or would they be strictly value added? Another issue would be to apportion employment strictly to the renewable energy sector, particularly when there are companies that employ engineers for example with many different tasks and responsibilities, among which a part is dedicated to renewable energy only.

7.1.2 Local empowerment and self-reliance

Lovins *et al.* (2002) indicates that 'many communities are preferring energy resources that are locally chosen, made and controlled – providing real economic benefits to electricity providers within their own vicinity'. In a sense, renewable technologies offer independence from fossil-fuel imports and price fluctuations (Evans *et al.*, 2009), and reduce the feeling that the communities' incomes are being transferred to distant outsiders. Lovins *et al.* (2002) indicate that "centralised resources tend to be built by large, bureaucratic institutions that are relatively opaque, slow, and inflexible as seen by outsiders. The impressions that such an organization is trying to impose its will on relatively powerless citizens can create a sense of injustice, reaction, and revolt". They continue to assert that 'distributed generation offers the scale to enhance the feeling and reality of political choice at a sufficiently local level to provide reasonable accountability';

"Technologies with a comparable scale to the community (where humans affairs tend to be organised, conducted, conceived) are better suited to community action and acceptance than those whose scale spans diverse communities and crosses jurisdictional boundaries. An appropriate degree of interdependence and independence may be better served by technologies whose scale fosters relative self-reliance than by those whose scale subsumes the needs of the community within a larger, more factitious and less cohesive area."

Although the focus of this statement is aimed at local distributed generation (e.g. small wind farm connected to local community), it can apply similarly to micro-generation where householders who decide to install microgenerators are empowering themselves and reducing their reliance on 'outside' factors.

In a study by Dobbyn and Thomas (2005), microgeneration was shown to have considerable impacts on shifting awareness, attitudes and behaviour. In their own words, Dobbyn and Thomas (2005) indicate that;

“Evidence suggests or indicate to the fact that either choosing to install micro-generation (active households) or living in a house where is has been installed (passive households) can significantly shift awareness, attitudes and behaviour. It seems that micro-generation provides a tangible hook to engage householders emotionally with the issue of energy use. The emotional resonance appears to come from an element of wonder that in this modern era we can make electricity and heat from such eternal and natural sources as the sun and wind (and waves). Householders described the sheer pleasure of creation and of self-sufficiency. “It’s like growing your own vegetables” was one of the oft-cited parallels. Some of our sample were only producing very modest levels of energy through their micro-generation technology, yet the behavioural impacts in terms of energy awareness and efficiency were often still considerable. Thus the findings from this research indicate that the qualitative impacts of micro-generation technology can be substantial, presenting a living, breathing and emotionally engaging face to energy consumption issues. In short, micro-generation can help bring the invisible to life.”

Again accounting for ‘local empowerment and self-reliance’ in the CBA for individual microgenerators is difficult to address quantitatively, and was therefore mentioned here qualitatively only. The issue will be returned to in Chapter 8.

7.1.3 Personal and psychological benefits

A final issue within the ‘social’ dimension of sustainability to be briefly and qualitatively discussed in the CBA of the three microgenerators is ‘psychological’ in nature. In specific, Lovins *et al.* (2002) points out that people may assign the following benefits to renewable distributed generation;

- *Higher esteem from neighbours, family and friends;*
- *Creating curiosity;*
- *Educating people on renewable energy and climate change Environmental; specifically in regards to ‘greening the neighbourhood’;*
- *Creating a personal green image.*

In a study involving 400 answered questionnaires and 111 ‘in-depth’ telephone interviews of ‘environmentally concerned’ green consumers, Caird *et al.* (2008) found that around 31% of “those who adopted solar PV said that using renewable energy or fuel gave them great pleasure and focused their attention on saving more energy. Some also saw their installation as a green status symbol: one user said of his solar panels that it is like flying a flag saying ‘we’re green’” (Caird *et al.*, 2008). Moreover, three-quarters of those interviewed with solar thermal systems installed, for example, said they were influenced into purchasing their systems from friends, colleagues or neighbours who have already these systems installed (Caird *et al.*, 2008), validating further therefore the above benefits cited by Lovins *et al.* (2002). However some

studies have indicated that microgeneration as a status symbol won't necessarily lead to the best installations for a given house as the underlying reasons for installing the microgenerators are socially-linked (Bergman *et al.*, 2009). A well known example of this is when one BBC radio interview in 2007 where the interviewee indicated the following; *"One of my friends has got a solar panel on the north-facing roof of her house. When I pointed out to her that's not necessarily the best place in the UK in order to be generating energy, she pointed out to me that I was not understanding why she's done it. The north-facing part of her house is the part that faces the street"* (Bergman *et al.*, 2009).

asked a householder why she had installed her PV on the northern-facing side of the street when the system would perform more optimally facing to the sun or south, to which she responded that the street is located to the north and she wanted everyone to see the installation (Bergman *et al.*, 2009).

Also, there are equally social downsides not mentioned here: microgeneration as a status symbol won't necessarily lead to the best installations for a given house; it could result in fit-and-forget, etc. (Bergman 2009; Bergman *et al.* 2009). Also, *energy literacy* is an important change.

Psychological benefits must be relatively considerable given the current performance of the microgenerators in terms of financial returns. Quantifying these benefits should be subject however to further research, particularly as those who purchase these systems currently, although relatively small in number, do so for some reason other than expecting financial rewards or rational cost-benefit analysis (excluding the newly proposed financial feed-in tariffs to be implemented from April 2010).

7.2 Network implications and the Supergen-HDPS Scenarios

The CBA and the financial appraisal of Chapters 5 and 6 respectively are focused on the microgenerators as individual systems installed by a householder. However, this is part of an overall assessment of highly distributed power systems (HDPS) carried out by the Supergen-HDPS consortium. Other Supergen consortia focus on the behaviour of power systems with many small distributed energy sources connected to them, and assess how to best control this distributed system through the device network interface which incorporates the control, communications and power electronics necessary to connect the distributed sources to the power supply system. These working packages have focused research on the consequence to the network, in addition to the required control techniques and technology, if either one of three different future scenarios are realized. In particular, a 'business as usual scenario', a 'low carbon' scenario, and a 'deep green' scenario were assumed up to 2050 (Jardine & Ault, 2008). Within these scenarios purposely leaning support for distributed generation, the uptake of distributed sources ranged from about 11% of total energy generation in the 'business as usual' (BAU) scenario, to round 40-45% in the 'low carbon' (LC) and 'deep green' (DG) scenarios (Jardine, 2006). Within these scenarios, PV and microwind make up a considerable expected amount, shown through total TWh in Figure 7.2.

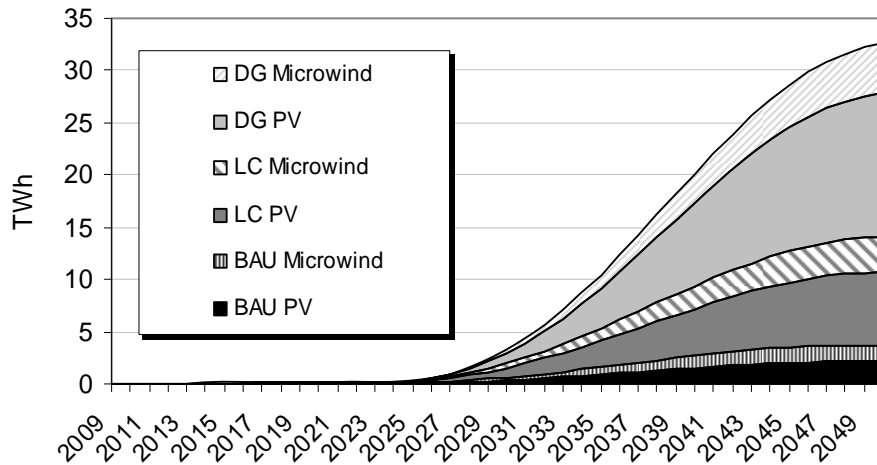


Figure 7-2 Microwind and PV uptake in Supergen HDPS scenarios
(Source: Jardine, 2006)

To gain a clearer perspective, the BAU foresees approximately 5% of total UK properties with an installation of PV and microwind respectively, while this percentage increases to 10% and 7% for PV and microwind respectively under the LC scenario, and 20% and 10% of households respectively for PV and microwind under the DG scenario. Solar thermal installations populate 10%, 12% and 25% of total UK domestic properties under the BAU, LC, and DG scenarios respectively; however they have no direct implications on the network.

The problem with this amount of distributed sources in an electricity supply system is that traditionally the distribution network was/is seen as being ‘passive’, simply delivering bulk power transmitted to it from conventional plants through higher voltage transmission networks (Lopes *et al.*, 2007). The current passive network (i.e., unidirectional power flow) fits well through this hierarchal electricity structure. However, it is considered not appropriate for a system within which a significant penetration of microgeneration (or distributed generation – which encompasses microgeneration) is to be expected.

When power flows occur in both directions with many sources and loads that have to be managed, monitored and controlled, issues arise with respect to voltage (additional microgenerators will increase voltage level in rural distribution networks), power quality (microgeneration can either increase or decrease the quality of voltage received by others in the distribution network), protection (protection of generation equipment from internal faults and protection of faulted distribution network from fault currents supplied by microgenerators...), and stability (transient and long term dynamic stability and voltage collapse) (Lopes *et al.*, 2007). These issues involve transforming the distribution system from being ‘passive’ to being ‘active’ (Strbac *et al.*, 2006) and are the focus of current research because the more microgeneration power outputs are connected to the distribution networks, the more widely the ‘fit and forget’ policy must be replaced by an active ‘integration’ to avoid the above technical, and commercial consequences (Lopes *et al.*, 2007). The ‘costs of changing the

distribution network are yet to be identified, although it is pointed out that the costs are outweighed by the benefits' (Lopes *et al.*, 2007).

Among these benefits are that microgeneration (and the larger component of distributed generation) can potentially 'shave off' peak demand and therefore curtail network investment needs in the face of load or demand growth (the extent of which depends on the distributed generator type (Mendez *et al.*, 2006).

There are other issues concerning the impacts of DG on conventional plant. With additional distributed generation, the efficiency of conventional plant may be affected due to the low capacity credit of distributed generation including the electricity supplying microgenerators assessed, requiring therefore spinning and standing reserves. In the 'traditional' electricity system where supply is mostly centralised, any distributed generators is simply connected to a unit and yet not integrated in the 'passive' system. Without an 'active system', distributed generation would contribute to energy output and consumption yet not to capacity, and therefore could lead to a decrease in efficiency of centralised power plants and increase the cost of energy generation, as stated by (Strbac *et al.*, 2007);

"If DGs and demand side management are not integrated in system operation, conventional generation will continue to be necessary for provision of system support services (e.g. load following, frequency and voltage regulation, reserves) required to maintain security and integrity of the system. This implies that a high level of DG will not be able to displace the capacity of conventional plant... Given that DG is connected to the distribution networks, maintaining the traditional passive operation of these networks and the philosophy of centralised control will necessitate increase in capacities of both transmission and distribution networks.

*On the other hand, by fully integrating distributed generation and demand side management into network operation as proposed in the "active future", distributed generation and demand side will take the responsibility for delivery of system support services, taking over the role of central generation. In this case distribution generation will be able to displace not only energy produced by central generation but also its controllability, reducing the capacity of central generation... To achieve this, the operating practice of distribution networks will need to change from passive to active" (Strbac *et al.*, 2007).*

These network issues are important to the economic CBA of Chapter 5 and are being addressed through the Supergen HDPS (and its renewal; Supergen Highly Distributed Energy Future - HiDEF), yet cannot be accounted for here because they require models or scenarios that are a function of increasing penetration levels and various mixes of distributed generation (including microgeneration), conventional generation mix, network structure and change, demand, and so forth. Furthermore, the CBA is performed for one system only, the individual impact on the network of which would be minimal.

7.3 Security of supply

'Security of supply' is usually the first catchphrase used in defining the objective of an energy system, along with concerns for climate change. Security of supply can be

defined in turn through several indicators, namely; (1) capacity or the safety margin between likely demand and available supply, (2) reliability or the probability that the capacity on the system is actually available to deliver supplies when required, (3) diversity or the ‘richness’ of an energy system through its reliance on many sources of energy, both technically and geographically diverse, and (4) price security or the ability to provide energy at reasonable prices to consumers (BERR, 2007).

The UK has been mostly self-sufficient in meeting its energy demand pre-World War II through wood and coal supplies, however became increasingly dependent on oil in the 1950s, 60s and 70s where oil imports reached approximately 50% of UK’s energy consumption (Wicks, 2009). The discovery of North Sea oil and natural gas from the late 1960s enabled the UK to become a net exporter of energy for most of the 1980s and 90s, yet has once again returned to its net importer status and in 2008 imported over 26% of its total primary energy needs (Wicks, 2009).

Wicks (2009) sets out recommendations as to how the UK government ought to go about securing its energy needs into the future beyond 2030 by coupling the concerns of climate change with energy security. They recommends the continuation and increase in investment in energy efficiency to reduce demand, praises the UK Renewable Energy Strategy and its objective of achieving 15% of energy from renewable sources (including a implied push for the Severn Barrage), advocates nuclear energy to contribute up to 35-40% of total electricity needs by 2030 and beyond, encourages carbon and capture technologies to sustain coal-fired plants, and recommends international initiatives to reduce global demand for energy which would effect the price of oil, particularly given the expected rise of energy demand post-recession (Wicks, 2009).

Beginning with capacity margin, the assessed electricity-supplying microgenerators do not score well in advancing this indicator of supply security, particularly given their intermittent resource which gives them low capacity credits³⁷, or the ability to displace conventional plants. Again, this fact is subject to many factors such as any future break-through in storage technologies for these systems which would enable them to deliver electricity at times when the wind is not blowing or the sun shining, and other factors such as the penetration levels of these systems and their geographic dispersion.

In terms of reliability, the assessed electricity-supplying microgenerators cannot be identified as reliable on the household level, again given the uncertainty as to when their respective resource will be available. However, when penetration levels increase and the network as a whole caters for this increase in an ‘active’ manner as discussed above, these systems could become reliable to a certain extent on aggregate, i.e., they would be expected to cater for a certain percentage of energy demand given their overall average known resource in the UK.

With respect to diversity, it is the ability of an electricity system to respond to disturbances or perturbations which deem it more ‘diverse’ and improves the security of supply. Diversity is “a combination of ‘variety’ or the number of categories into

³⁷ Capacity credit is a measure of the amount of load that can be served on an electricity system by intermittent plant with no increase in the loss-of-load probability (UKERC 2006).

which the quantity in question is portioned (e.g., gas, coal, wind, and so forth), ‘balance’ or a pattern in the spread of that quantity across the relevant categories and ‘disparity’ or the nature and degree to which the categories themselves are different from each other” (Grubb *et al.*, 2006). One of the several (and simpler) indices for measuring diversity is the Shannon-Weiner (S-W) index which includes ‘variety’ and ‘balance’ yet not ‘disparity’. The S-W index measures diversity by dividing generation according to fuel type according to Equation 7.1 (Grubb *et al.*, 2006).

$$\sum_{i=1}^I - p_i \ln(p_i) \quad 7-1$$

Where p_i is the proportion of generation represented by the i th type of generation. The S-W index is illustrated in Figure 7.3, showing how the diversity index for n equal independent contributions changes as n grows.

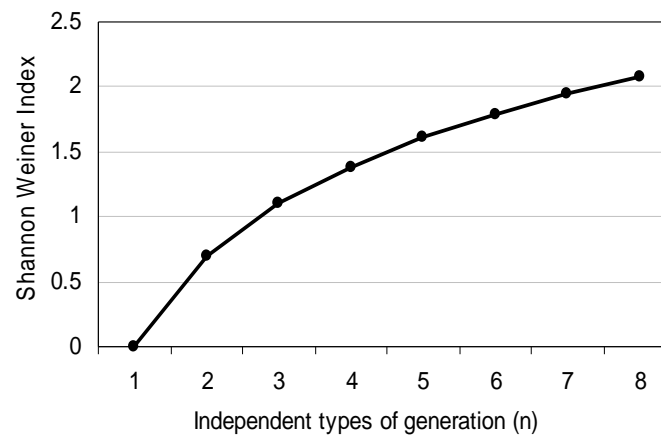


Figure 7-3 Shannon-Wiener index
(Source: Grubb *et al.*, 2006)

A S-W value of below 1 indicates a system that is highly concentrated and dependent upon one or at most two sources which threaten security of supply, whereas a S-W value above 2 indicates a system with numerous sources which could be considered relatively secure (Grubb *et al.*, 2006). There has been considerable debate as to whether to consider large-scale wind energy, for example, as an independent source of generation given its intermittent nature and capacity credits of around 11-30%, depending on the penetration levels and geographic concentration of wind energy sources (UKERC, 2006). Similar arguments can be had for microwind and PV. However, PV and microwind (just as large-scale wind) can be considered as independent sources of generation which would enhance the diversity of supply, given their independence from other energy sources and contribution to security of supply, and given that significant uptake of these systems are required to include them as ‘equal independent’ generators as other sources. Moreover, one microwind turbine or one PV system could be considered to have a high ‘diversity’ weight for an individual householder, at least when 40% and 50% of electricity produced from these systems are said to be consumed in-house (see Chapter 6).

Finally, the microgenerators as individual small-scale systems have limited impacts on UK energy price security which are based mostly on international oil prices. In fact, for the short-to medium term, they may impose a slight increase in prices to all consumers as the feed-in tariff suggested in Chapter 6 will be paid as an increase in overall price charged for electricity to all consumers. In the longer term, with more expected penetration levels of microwind and PV systems, and with their expected reduction in capital costs (see next section) and subsequent support tariff levels towards no support (see Chapter 6), these systems can play an important role in reducing demand for ‘imported’ electricity, therefore down-ward pressuring electricity prices.

7.4 Further monetized attributes

Two further attributes are described in turn through this section; double dividend effects and learning effects. These attributes are monetized yet are omitted from the original CBA given that further research is required for the first (double dividend effects), and due to the fact that no reference can be made to the latter due to the fact that it is a simple and author-established method for accounting for the learning effects.

7.4.1 Double-Dividend

The ‘double dividend effect’ occurs when a small scale domestic renewable systems generating electricity induces overall demand reduction, particularly if accompanied by a smart meter (yet not a pre-condition). The latter may assist the double-dividend effect given that visible monitoring devices are required to compare a domestic householder’s electricity consumption and the current production from the renewable energy system. This could then induce behavioural changes on two fronts; shifting load to when the microgenerator is generating significantly and reducing overall consumption of electricity.

In one study analysing the double-dividend effect in 100 UK households whom have installed PV systems, the results showed PV systems could induce a 6% reduction in overall electricity consumption (Keirstead, 2007). In a report by the House of Commons Trade and Industry Committee, the report espouses the evidence from other countries that ‘consumption can fall by over 6.5% in households that have smart meters installed’ (House of Commons, 2007). Yet the latter study was referring to reduction of electricity only through smart metering as opposed to electricity reduction from the combination of PV and smart metering.

Assuming the 6% value from Keirstead (2007), and given that the average annual electricity consumption of a UK household was assumed to be 4,000 kWh per annum, the double dividend effect entails a reduction of yearly consumption by approximately 240 kWh. This entails a saving of about £30 per annum if the current (2009) average retail price for electricity is assumed. The total potential benefits over the lifetime of a PV/BIPV system are shown in Table 7.1.

System	Total	Total	Smart	Net benefits	Net benefits
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	benefits (£) @ 3%	benefits (£) @ 5%	meter cost (£)	(£) @ 3%	(£) @ 5%
μ-wind	358	312	100-200	158-258	112-212
PV	522	423		322-422	223-323

Table 7.1 Potential double-dividend implications for PV/BIPV systems

Approximately £100 - £422 of additional net economic benefits (excluding environmental benefits) could be realised from a PV system through the double-dividend effect. The addition of a smart meter is not a pre-requisite for the effect, yet was included given its benefits in visualising the electricity supply and demand changes. The benefits in Table 7.1 are only pertained to the smart meter in combination with the PV, meaning that installing the smart meter will undoubtedly have other benefits such as avoided manual meter readings (that may save substantial income for energy suppliers or to householders if that saving is passed on), better customized time-of-use tariffs (that may assist in lowering peak demand), and reduced electricity theft due to meter tampering (House of Commons, 2007).

However, the benefits were not included directly in the economic analysis of Chapters 6 and 7 for several reasons which the Keirstead (2007) study itself alluded to. In specific, the ‘double dividend effect’ leads to many questions needing further research such as ‘how long will this effect take place?’, ‘what are the influences of different types of monitoring devices?’, ‘hasn’t the potential of post-PV energy-saving been partially limited by the extensive measures taken by these households before installation?’ (Keirstead, 2007). Therefore the benefits of the double-dividend effect as applied on the microgenerators is considered subjective, dependent to the habits of the householders in question, and it could therefore not be guaranteed (Hammond *et al.*, 2009). Moreover, no reference has been found documenting the double dividend effect for microwind systems, perhaps given the unpredictability of their electricity supply whereas PV can be relatively more predictable given the knowledge of general weather conditions.

What is certain is that the combination of home-grown electricity with smart meters fits comfortably with some of the criteria set forth in Chapter 1 concerning ‘sustainable energy’. In specific, smart metering will provide the monitoring tools to better enable householders to assess their energy consumption versus supply from their renewable systems. This would enable householders to adjust their behaviours accordingly. However, a verification of long-term actual electricity reductions allocated solely to the microgenerator-smart metering combination remains to be further verified by research and therefore was not included in the original CBA.

7.4.2 The learning effect

The CBA and the financial appraisal implemented in Chapters 5 and 6 capture a snapshot of the current economic and financial situation of the assessed systems given certain likely future scenarios associated with parameters such as environmental damage cost assumptions for the CBA and future electricity and fuel prices for the financial appraisal. Sensitivity analysis allowed for parameters that will likely influence the NPV and the BC ratio to change, however the most important parameter to influence the economic and financial situation of the microgenerators are changes

to their respective capital costs. The high capital costs of the systems are indicated to be a primary barrier to market (Allen *et al.*, 2008b), and therefore the alleviation of this barrier is widely acknowledged to be one of the most effective ways to spur the uptake of these technologies. The financial support mechanisms like the FITs and/or the LCBP grants are instituted to reduce this barrier, and as these technologies are considered relatively ‘immature’, capital cost reductions are expected through their so-called experience curves. These cost reductions are confidently expected in the UK as they were reflected in the degression of the FIT structure for the microgenerators outlined in Chapter 6.

Experience curves are often used to assess the cost reduction potential of new technologies. The cost reductions involve the total cost (labour, capital, administrative, research and marketing) brought about through changes in production (process incremental innovations, learning effects and scaling effects), changes in the product itself (production incremental innovations, product redesign and product standardisation), changes in input prices and/or changes in the entire socio-technical system such as the creation of effects of industrial clusters and networks (NEEDS, 2006a). The experience curve describes how unit costs decline with cumulative production, specifically indicating that costs decrease by a constant percentage with each doubling of the total number of units produced (NEEDS, 2006a). They provide ‘a simple, quantitative relationship between price and the cumulative production or use of a technology’ as there is ‘overwhelming empirical support for such a price-experience relationship from all fields of industrial activities, including the production of equipment that transforms or uses energy’ (IEA & OECD, 2000). The experience curve could be considered a measure of the efficiency of the feedback mechanisms or the learning loop for the system assessed. In other words and in a competitive market, *“the learning system considers the effects of output on its environment and adjusts its internal working to improve performance. The internal adjustment is based on earlier experience of transforming input to output, and the experience curve defines the measure of performance as the ratio of input over output... The model implies that learning is the result of activities producing outputs which are assessed by a competitive environment and not through laboratory R&D alone”* (IEA *et al.*, 2000). The basic learning model does not make any hypothesis about the processes going on inside the learning system, yet considers this system as a black box for which only input and output can be observed (IEA *et al.*, 2000).

The general learning function form for experience curves could be given by Equation 7.2 (Mackay & Probert, 1998).

$$y_x = ax^{-b} \text{ (or logarithmic version); } \log y_x = \log a - b \log x \quad 7-2$$

Where ‘ y_x ’ is the cost (or labour input) required to produce the x^{th} unit of production, ‘ x ’ is the cumulative production up to and including the x^{th} unit, ‘ a ’ is the estimated cost required to produce the first unit, and ‘ b ’ is the learning parameter (Mackay *et al.*, 1998). The logarithmic version is an oversimplification of reality which represents the experience curve linearly.

The concept of experience curves should not be taken as an established method, yet more of a correlation phenomenon which has been observed for several technologies

(NEEDS, 2006a). They should be used with caution only to provide general guidance of the expected future trends of technology costs as opposed to being forecasting models. Experience curves can be developed according to different system approaches, may describe different parts of a technology system, and may be different for different time frames (NEEDS, 2006a).

7.4.2.1 Experience curves for microgenerators

Many literature sources indicate or quote experience curves for various energy technology types, whether distributed or centralised and conventional or renewable (including low-carbon technologies). From the onset, a clear characteristic can be made in that ‘newly emerged technologies that have a small market share have much larger potential for cost reductions relative to established technologies’ (PIU, 2001). For the particularly assessed microgenerators, experience curves range from 18-20% for PV (EST *et al.*, 2005; IEA *et al.*, 2000), 18-28%³⁸ for microwind and 8-10% for SHW systems (EST *et al.*, 2005; Hinnells, 2005). In other words, for every doubling of cumulative capacity, capital costs for PV are expected, as guidance only, to drop by 18-20%, while for microwind an 18-28% cost reduction could be expected, and only 8 – 10% for the SHW system, as the latter technology is considered relatively mature.

The expected cumulative production and installation of the assessed microgenerators from the present into the future is subject also on many uncertainties that will depend on which developmental road the UK would take in particular, and the world in general. What is certain is that the uptake of the assessed microgenerators will be dependent on how the production and price levels of oil and gas evolve, on demand for energy, on carbon emission impacts and counter policies, on governmental support and investment (and private sector investment) in renewable energy, and so forth. The International Energy Agency and the European Commission (EC) both project several future energy outlook scenarios from the present to 2030-2050, each dictated by its own assumptions on economic, technological, and environmental (policy) trends (EC, 2006; IEA, 2006). The IEA and EC reports cluster the technologies in their respective reports, focusing for example on ‘solar’ energy or on large-scale ‘wind’ which may not be similar to the specific microgenerators. The EST *et al.* study (2005) on the other hand models the specifically assessed microgenerators from 2005 to 2050, adopting three possible cumulative growth-experience curve rate scenarios; low, median or high. Adopting the median expected growth rates, the assessed microgenerators’ expected capital costs (mean values) and corresponding financial NPV (given the maximum output assumptions) are presented in Figure 7.4.

³⁸ The EST *et al.* (2005) assumes, on average, that the progress ratio for microwind is approximately 28% and yet decreases by 2050 to 5%. Therefore, the 18% value would be adopted.

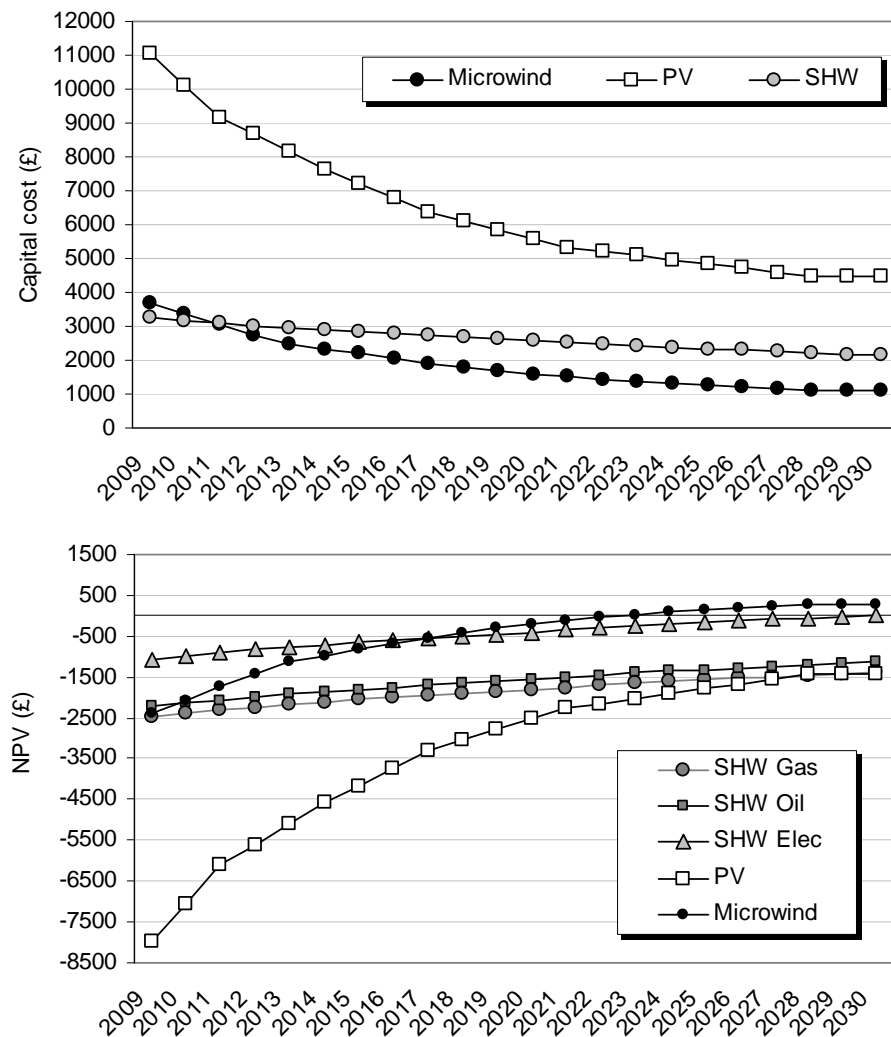


Figure 7-4 Expected capital cost reductions and corresponding financial NPV of the microgenerators under mean capital costs and maximum output scenario

The PV (and BIPV) and microwind systems have the most to gain still from production and expansion. The expected capital (with installation) costs of PV may drop to £4800 by 2030 from its current approximate cost of £11,000. The microwind system will experience a possible cost reduction of approximately 70% by 2030. The SHW system will be subjected to a possible capital cost reduction of about 35%, reaching just over £2,000 by 2030. The microwind would begin to achieve a financial NPV greater than 0 by 2023, and the SHW displacing electricity would break even by 2030. The PV system would experience substantial improvements in the NPV, yet not enough to enable it to achieve a positive NPV - *ceteris paribus*. When these are taken against possible alternative scenarios with higher prices for electricity and fuel, they will surely become more attractive in financial terms.

With respect to the economy-wide benefits of potential reductions in capital costs, Figure 7.5 illustrates the NPV of the microgenerators under the commencing mean capital cost assumption, and the maximum energy output case, using approach 2 as a guidance to the environmental damage benefits. It is evident that microwind will

enable a positive return over its lifetime by 2011 while PV will return a positive NPV by 2018.

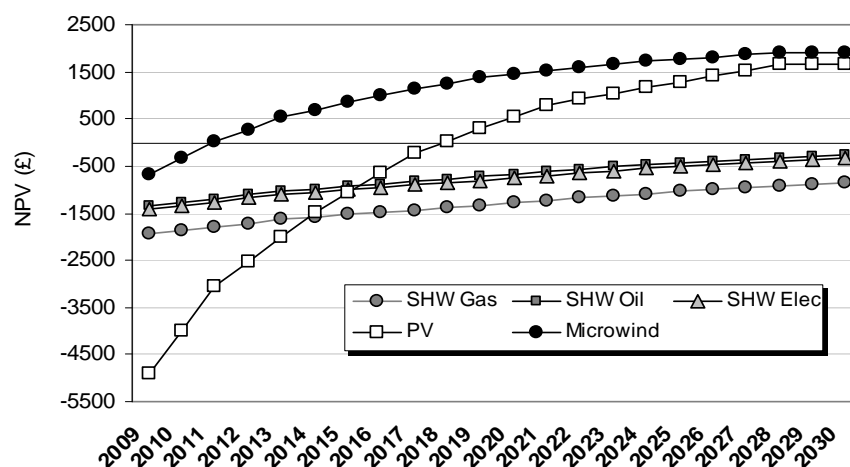


Figure 7-5 Expected economic NPV of the microgenerators under mean capital costs, maximum output scenario, and approach 2 environmental damage estimation

Hammond *et al.* (2009) have shown similar results for the mean output scenario for the BIPV system. In specific, “if the mean assumptions of production output growth and learning rates from the EST *et al.* (2005) report are adopted to get the yearly reductions in capital costs of the systems from the present to 2050, the expected capital costs of BIPV are expected to drop considerably and gradually into the future, yielding improved net present values until break-even would be expected in year 2019...” (Hammond *et al.*, 2009). This prospect, if realised, would offer an attractive option for the UK domestic sector given the upcoming regulation which requires all new build UK homes to be zero carbon in operation by the year 2016 (Hammond *et al.*, 2009).

The economic NPV for SHW systems displacing gas and oil have improved significantly due to capital cost reduction as compared to the financial appraisal results. This can be attributed to the inclusion of environmental benefits. However, taking the society-wide costs and benefits from displacing electricity by a SHW system yields a lower NPV result than the financial appraisal for individual households due to the fact that the average value for hot water was lower than the retail price of electricity.

7.4.2.2 Experience curves and current microgenerators

The analysis in the preceding section targets the assessed systems in future years, and this is usually the case for presenting experience curves. In doing so, a general indication of the future prospects of the microgenerators is presented. However, absent from the literature are examples of how to apportion these cost reductions to the current microgenerators or any other renewable energy system in this instance. The section below proposes therefore a simple yet novel methodology for doing so, first diagrammatically, and then algebraically.

Consider Figure 7.6, where a hypothetical technology ‘M’ is presented.

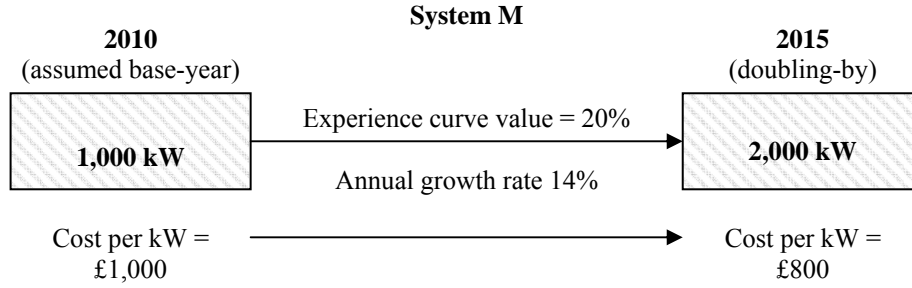


Figure 7-6 Methodology for accounting the experience curve externalities

The methodology presented in Figure 7.6 will have to begin by assuming two discrete dates, which is an assumption held already by experience curves in general. If the baseline capacity, date and cost are 1000 kW, the year 2010 and £1,000/kW respectively, and the growth of system ‘M’ will lead to doubling of global capacity by 2015, then given an experience curve value of 20%, capital costs of system M are expected to become £800/kW by the end of 2015. The first year after the cost reduction have occurred, i.e. year 2016, the systems installed in that year will therefore be £200/kW cheaper than 2010. If the growth rate is assumed constant at 14% for 2016, then 280kW of systems are installed in 2016. The total benefit of the 1000 kW of new ‘M’ capacity installed between 2010 and 2015 is equal to 280 kW x £200, or £56,000. Installing 1kW therefore has assisted in £56 of savings or total reduced costs and should be attributed to that 1kW system which was added somewhere between 2010 and 2015.

Equation 7.3 illustrates the positive learning externality saving per unit algebraically.

$$\left[\frac{(X_{D+1}) (C_o) (EC \text{ value } \%) }{(X_D - X_o)} \right] \frac{1}{(1 + r)^{t_{D+1}}} \quad 7-3$$

Where X_o is the initial capacity at baseline date, X_D is the capacity at the year of doubling, X_{D+1} is the capacity installed in the first year after doubling only, C_o is the per unit cost at the baseline date, r is the discount rate, and t_{D+1} is the time, in years, after which doubling takes place (inclusive of the first year after doubling).

According to the assumptions of growth rates and experience curves presented above, adopted mainly from the EST *et al.* (2005) report, and taking 2008 as the baseline year, then in 2011 and 2012 the first doubling of global capacity of microwind, and PV/BIPV and SHW systems are expected, respectively.

Approximately 13 GW of PV/BIPV systems and 145 GW_{th} of SHW systems exist cumulatively in 2008 (REN21, 2009). For microwind, no information was available as to the global cumulative capacity, however given that the UK is a leader in the

microwind industry (as opposed, for example, to the PV industry where PV panels are mostly purchased from China or other places³⁹), exporting 50% of its systems (BWEA, 2009), the growth of UK microwind systems is taken as proxy for global growth. Figure 7.7 illustrates the baseline capacity, experience curve percentage, growth rates (and doubling years) and the expected reduction per unit of kW for our assessed systems.

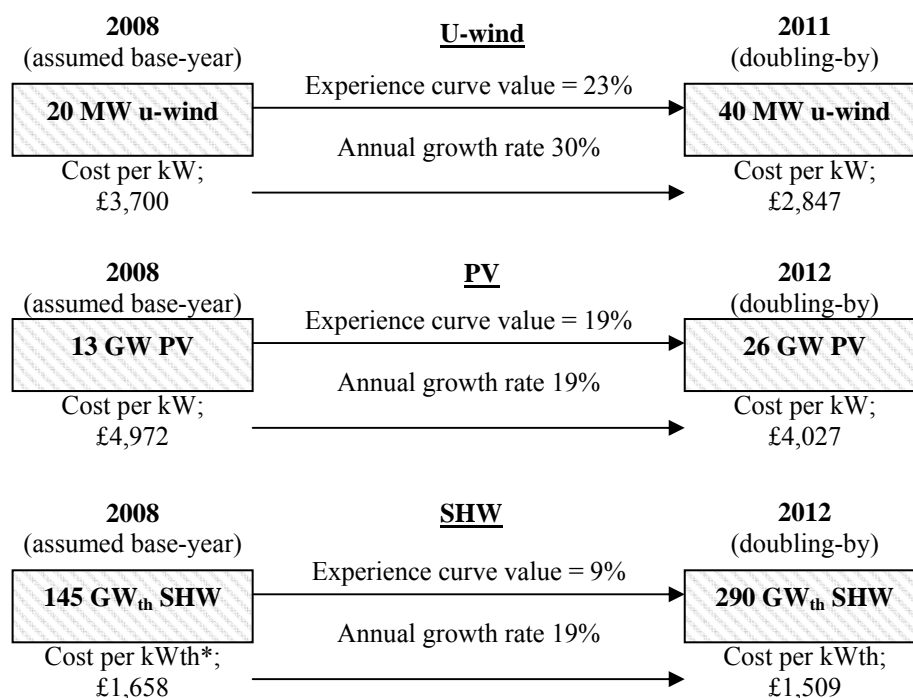


Figure 7-7 Experience curve externality benefits from PV/BIPV and SHW systems

The microwind growth rate is assumed at 30% (EST *et al.* 2005; BWEA, 2009), leading to an additional installed capacity for the first year post 2011 (i.e., 2012) of 12 MW. The average growth rate of PV on the other hand is indicated to be 19% (conservative estimate), prompting 4.94 GW of additional installed capacity for the first year post 2012 (i.e. 2013). For SHW this value will be 55.1 GW given also a 19% annual growth rate assumed in 2014.

The total saved costs due to the installations from 2008-2011 for microwind, in 2012, is £10.236 million, or a £512 saving per kW. For the 600W assessed system, this could be assumed to be £307, or £281 when discounted at 3% discount rate.

The total saved costs due to the installations from 2008-2012, in 2013, is £4.6683 billion for PV/BIPV, and £8.2099 billion for SHW systems worldwide. The impact from 1kW of production anywhere between the baseline date and the end date is £360 for 1kW of PV and BIPV systems, or £756 for our assessed 2.1 kW_p PV/BIPV system, and £56.6 for 1kW_{th} of SHW added, or £110 for our 2.8 m² SHW system

³⁹ Out of more than 7274 MW world PV cell production in 2008, the UK's share in this manufacturing was estimated to be 0.034% only (IEA PVSP, 2009).

(given a conversion factor of 0.7 kW/m^2). These values depreciate to £672 and £98 when discounted at 3%, respectively for the PV/BIPV and SHW systems.

7.4.2.3 Limitations of experience curves

Although experience curves have been assumed in official UK policy documents such as the UK Government Energy Review (DTI, 2006b) and the Stern Review (Stern, 2006), with subsequent implications for the outcome of cost assessments, significant limitations and concerns with their application continue.

Jamasb and Kohler (2007) survey the literature quantifying experience curves in the energy sector from the 1980s to the present, noting that ‘estimates associated with different technologies and time periods span a very wide range, from 3% to 35% cost reductions associated with a doubling of output capacity’, examples of which are shown in Figure 7.8 (Jamasb & Kohler, 2007).

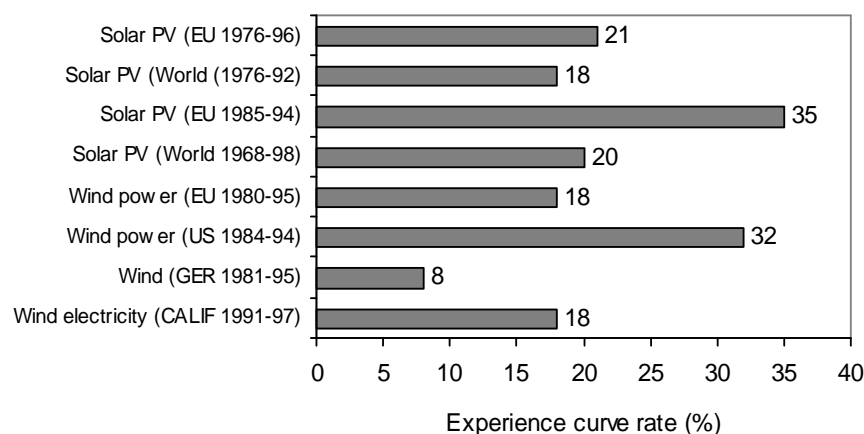


Figure 7-8 Experience rates (%) in wind and solar production technologies
(Source: Jamasb & Kohler, 2007)

Figure 7.8 shows that even for the same technology types experience curve percentages differ depending on the geographical location of the assessment and depending on the baseline year adopted. This reflects a lack of accurate and detailed data on the experience curve issue, particularly given the fact that experience curves is a ‘cumulative’ or global concept, and given that they are really ‘rooted in the historical development of technologies’... yet the ‘future development path of technologies is likely and even expected to be somewhat different from their progress in the past’ (Jamasb *et al.*, 2007).

A further critique of the experience curve concept argues to the fact that an experience curve really should be a two-factor curve (in the least), instead of a single factor one in order to better capture the difference between the research and development (R&D) stage of a technology and the ‘market pull’ where the technology is taken up by the market (Jamasb *et al.*, 2007). Jamasb and Kohler (2007) explored the issue and results ‘indicate that single-factor learning curves overestimate the effect of learning-by-doing in general and that of new and emerging technologies in particular, given that much of the cost reduction occurs potentially in the R&D stage before dissemination

of technology, and the later contribution of market pull contributes as well yet not to the same magnitude deemed by single-factor learning curves (Jamassb *et al.*, 2007).

Thirdly, experience curves were assumed to cover both capital and installation costs in the CBA and the financial appraisal of Chapters 5 and 6. Although there will be experience benefits in installing energy sources, particularly renewables and microgeneration, the learning ratio is by no means similar to that of the capital costs. Bergman and Jardine (2009) have indicated that installation costs “*are expected to show an ‘institutional learning curve’ which is country specific, or even company specific. In other words, as installers gain experience, they will find cheaper supply chains, and their installation practice will become more streamlined and faster, reducing the installation costs accordingly...*” Combining both capital and installation for the microgenerators as presented in this thesis is therefore a limiting factor, and a more realistic or accurate scenario would have to separate the two influences of global cumulative supply and local installation characteristics.

Finally, it has been observed that for the first two years after the LCBP has been initiated, there was no drop in prices of microgeneration in the UK (Bergman & Jardine, 2009). One explanation for this is due to the fact that the UK microgeneration market has too few players to be truly competitive and is operating within what is known as the ‘price umbrella’, described below (Bergman & Jardine, 2009);

“The ‘price umbrella’ describes what happens to the price charged for a product versus its cost of production as the market matures. Initially, the market leaders set the price lower than cost to help establish the market. As costs reduce, however, there is no incentive to reduce the price charged, as there is little competition. This area, where prices remain constant and high, is known as the price umbrella and is indicative of a market with only a few players. As the market grows the situation is unstable with many actors operating with high profit margins, and eventually a shakeout phase causes prices to fall and margins to reduce. Finally there is a stable phase, where a competitive market exists and price more accurately reflects costs.”

According to the price umbrella, the reduction of price asked by manufacturers and suppliers for the assessed microgenerators will not, therefore, follow a smooth trend of reduced costs to follow global cumulative uptake, yet will possibly remain on the high side until this ‘shakeout’ phase jilts the market and lowers the costs considerably.

7.5 Qualitative assessment of the microgenerators; conclusion

This Chapter outlined other important attributes that may play a key role in the judgment as to whether the assessed microgenerators are worth it or not in the UK context. Perhaps these qualitative attributes are the reason why people are currently purchasing the microgenerators, although few in numbers. It could be that already by assuming a discount rate of 8% in the financial appraisal, these attributes have been internalised, given that some studies estimate a 30% ‘implicit’ discount rate for household energy-related investment such as microgeneration (Watson *et al.*, 2008).

Nevertheless (and for CBA which is a society-wide analysis), the above attributes are important to consider in any CBA targeted at microgeneration, even qualitatively, in order for the analysis to be complete.

Employment gains are expected from the microgenerators, as are ‘local empowerment and self-reliance’ feelings, which can be grouped into the psychological realm of benefits. Double-dividends have also been shown to occur, yet again, long-term research is required to adequately state that such affects don’t, for example, erode with time. Last, positive externality values are present and the microgenerators’ capital costs will go down. These positive cost externalities have been quantified above, however given that the author has not come across such a technique, the analysis was indicated in the qualitative part of the CBA, pending peer-review.

Chapter 8 attempts to combine all the attributes used in the CBA, both qualitative and quantitative, as inputs into another decision-aiding tool. A simple multi-attribute ranking technique, which is a form of multi-criteria evaluation, is performed.

8 Microgenerators in the Wider UK Energy Context

The Stern Review on the economics of climate change has summarised its' main findings through several key points, some of which indicate that;

- *There is still time to avoid the worst impacts of climate change, if we take strong action now;*
- *Climate change could have very serious impacts on growth and development, estimated to cost the equivalent of 5% of global GDP annually, and up to 20% of GDP annually if the 'wider range of risks and impacts' are taken into account;*
- *The costs of stabilising the climate are significant but manageable; delay would be dangerous and much more costly;*
- *A range of options exists to cut emissions; strong, deliberate policy action is required to motivate their take-up. At least 60% of the power sector needs to be decarbonised by 2050 for atmospheric concentrations to stabilise at or below 550 ppm CO_{2e}...*

The UK is apparently stepping up to the significant challenges and required action on CO_{2e}, as outlined by the main findings of the Stern Review. It has set itself the objective of reducing its carbon dioxide emissions at least 80% by 2050 against a 1990 baseline and with real progress to be made by 2020 (OPSI, 2008), and has set itself the challenge of delivering up to 30% of electricity needs and 12% of its heat from renewable sources by 2020 (DECC, 2009i). Given that the UK domestic building sector, as mentioned in Chapter 1, constitutes currently around 30% of the UK's final energy demand and about 23% of greenhouse gas (GHG) emissions, the sector can therefore play an important role in carbon dioxide (CO₂) abatement. Furthermore in Chapter 1, microgeneration has been alluded to as being capable of contributing to the lowering of GHG emissions from the domestic sector, as well as capable of assisting in other publicized objectives, such as maintaining reliable energy supplies, promoting competitive markets and combating fuel poverty (Allen *et al.*, 2008b). The EST *et al.* (2005) and the Supergen HDPS Consortium (to which this thesis contributes to) have indicated that a substantial part of total UK domestic energy requirements can be met through microgeneration. However, the economics of the assessed microgenerators have shown that the systems are currently uncompetitive, and would require substantial government-led support to enable them to break-even (based on the NPV and B-C ratio indicators).

Therefore, an important aspect to observe would be to assess if the assessed microgenerators would be able, or *should be* supported to be able, to contribute to the reduction of GHG emissions (among the other above stated objectives) in the UK as advocated by the EST *et al.* (2005) and the Supergen HDPS Consortium.

Two new and additional decision-aiding tools; cost-effective analysis (CEA) and a simple multi-attribute rating technique (SMART) are applied in this chapter to analyse the relative merits of the assessed microgenerators in relation to other energy generating sources in the UK. These additional tools are also utilised here precisely because there was a significant qualitative part in the CBA, which could be *said* to render the NPVs (or BC ratios) obtained for the various microgenerators as incomplete indicators of these system's value to society.

Furthermore, and for comparative purposes only, a cost-benefit analysis of a large onshore wind farm is assessed on a kW basis using environmental approach 1. This exercise will better illustrate the economies-of-scale involved in wind production.

8.1 Alternative decision-aiding tools

8.1.1 Decision making in the ‘integrated appraisal toolkit’

The integrated appraisal approach adhered to in this thesis and advocated by Allen *et al.* (2008a and 2009), Hammond *et al.* (2009a and 2009b), and El-Fadel *et al.* (2009), all reproduced in Appendix 8, is an innovative technique which required a uniquely interdisciplinary procedure to implement.

However even with the various different techniques applied in this study, particularly energy analysis, life-cycle assessment, and cost-benefit analysis, a decision as to whether or not to advocate the installation of the assessed microgenerators in order to assist in meeting the challenge set forward by the UK Renewable Energy Strategy is still, to a certain extent, ambiguous.

Taking independently, the ‘energy analysis’ of the microgenerators, or any other energy source, can undoubtedly provide clear recommendations through the ‘energy gain ratio’ (EGR) or the ‘energy payback ratio’ (EPR), for example. In Allen *et al.* (2008a and 2009) and Hammond *et al.* (2009a and 2009b), it was shown that all the assessed microgenerators pay-back their energy’s investment well within their lifetimes, particularly when assessed against the unit of energy displaced (i.e., the displaced payback ratio). In El-Fadel *et al.* (2009), several energy technologies were compared through the EGR based on Gagnon *et al.* (2002), and inference is made to the benefits from moving towards the use of natural gas, hydro, and renewables, respectively (and strictly in energy terms).

Similarly, LCA could provide clear recommendations on environmentally comparative grounds, or hint to environmental implications through normalisation. Comparative environmental impacts of the production and lifetime operation of the assessed systems have yielded positive environmental impact results in Allen *et al.* (2008a) and Hammond *et al.* (2009a), or when normalised against European ‘people emission equivalents’ in Allen *et al.* (2008a and 2009) and Hammond *et al.* (2009a and 2009b). This provides decision-makers with clear information. Elsewhere in the literature, conventional and renewable energy sources are compared in Gagnon *et al.* (2002), for example, in terms of life-cycle emissions of carbon, sulphur dioxide and nitrogen oxides, and decision-making based on the relative or comparative performance of these sources, on those environment terms, can easily follow suit. Even when or if one impact category, such as carbon, is worse than another, say sulphur dioxide, when comparing two technologies, a decision can still be reached if further assessment, such as the use of end-point LCIA methods (e.g. Eco-indicator 99 LCIA method applied in this study), are utilized.

On the other hand and in general, CBA may or may not provide a clear-cut answer as it involves many categories or criteria over and above the financial accounts. It is not restricted to one category, like ‘environment’ or ‘energy’, yet involves economic, social, and environmental attributes. As Figure 2.9 of Chapter 2 indicates, more often

than not, the qualitative part remains a necessity which may undermine the NPV criterion and deem it incomplete, as was the case for the assessed microgenerators in this study. The CBA study could stop here, rejecting the installation of the assessed micro-generators based on the NPV indicator. However, the actual choice as to whether or not to encourage the deployment of the microgenerators will rest on decision-makers weighing also the qualitative or non-monetized attributes which were excluded or omitted from the NPV indicator. They can do this through the use of simplified mental strategies, or heuristics, or through the application of alternative decision-aiding tools that enable the aggregation of quantitative and qualitative attributes simultaneously (Goodwin & Wright, 2009). The decision will also need to be done in context of other competing energy sources.

In this study's case, the NPV indicator clearly gives a result as a "no-go" for most of the assessed microgenerators, and therefore the decision-maker will need then to weigh for him or herself whether or not the non-quantified parts of the analysis are enough to overturn the NPV rule. However, this would undermine the rationale or motivation for using an 'integrated approach' in the assessment of projects, technologies, or particular alternatives. Therefore the study has opted to use two more tools; cost-effective analysis (CEA) and simple multi-attribute analysis (SMART) in order to shed more light on the performance of these technologies in strict comparative economic terms (CEA), and through the integration of the many qualitative and quantitative categories used throughout this thesis (SMART).

In fact, Allen *et al.* (2008a) refer to multicriteria evaluation (MCE) as a tool into which thermodynamic analysis, LCA, and CBA feed results into (see Figure 1.2). For the study here however, a SMART is implemented to briefly give an indication of whether or not the assessed microgenerators, particularly the PV/BIPV and SHW systems (given that microwind has a positive NPV under high-wind energy resource area with low capital costs), could score enough aggregate points relative to other energy sources to deem them worthy of government support.

8.1.2 Cost-effective analysis (CEA)

The CBA of the microgenerators yielded sufficient results as to the performance of each assessed system in and by themselves through the NPV and/or the BC ratio indicators. However, the results do not put the systems in context or enable a comparative view of where these systems are in terms of their overall competitiveness and potential, particularly given other more established heating (and hot water) and electricity-supply technologies. Therefore, a CEA is warranted, where several electricity generating sources are compared with the microwind and the PV (and BIPV) systems, and relevant heating technologies compared to the SHW system.

An intensive literature-based research was implemented late 2007 and beginning 2008 to obtain the necessary values to calculate the levelised cost of various technologies in the UK context. The levelised cost methodology "*calculates electricity generation costs on the basis of net power supplied to the station busbar, where electricity is fed to the grid..., and discounts the time series of expenditures and incomes to their present values in a specified base year by applying a discount rate*" (NEA *et al.*, 2005). Equation 8.1 presents the levelised cost methodology (NEA *et al.*, 2005).

$$EGC = \frac{\sum \left[\frac{(I_t + M_t + F_t)}{(1+r)^t} \right]}{\sum \left[\frac{(E_t)}{(1+r)^t} \right]} \quad 8-1$$

Where;

EGC: Average lifetime levelised electricity generation cost
I_t: Investment expenditure in the year *t*
M_t: Operations and Maintenance expenditures in the year *t*
F_t: Fuel expenditures in the year *t*
E_t: Electricity generation in the year *t*
r: Discount rate

In other words, the levelised lifetime cost per kWh generated is the ratio of total lifetime expenses versus total expected outputs, expressed in terms of present value equivalent. This cost 'is equivalent to the average price that would have to be paid by consumers to repay exactly the investor/operator for the capital, operation and maintenance and fuel expenses, with a rate of return equal to the discount rate' (NEA *et al.*, 2005).

Appendix 5 points to the references surveyed for the information required for these estimations. A wide-range of values was obtained for each cost category input within each surveyed technology such as; capital costs, operating and running costs, and expected energy outputs. Table 8.1 presents the findings with respect to capital costs, operation and maintenance costs (including fuel costs where applicable), and expected output for electricity generating sources in the UK.

	Capital cost (£/kW)	O&M (£/kW)	Output (kWh/kW)	Lifetime assumed
CCGT (combined cycle gas turbine)	360 - 440	150 - 260	7446 - 7884	35
Coal	700 - 1000	200 - 260	7446 - 7884	35
Nuclear	1170 - 1435	131 - 146	7446 - 7884	40
Onshore wind	700 - 840	35 - 47	2102 - 2716	20
Offshore wind	1300 - 1600	40 - 80	2628 - 3066	20
Hydro	1124 - 1774	40 - 65	3066 - 3373	25
Marine	1400 - 2875	65 - 110	2500 - 2890	15
PV	4000 - 6000	10 - 30	815 - 1200	25
Microwind	3000 - 3500	30 - 50	1000 - 2000	15

Table 8.1 Capital, operation, maintenance costs and output of various electricity generating sources per kW capacity

The levelised cost estimates for the electricity generating sources are estimated from the values of Table 8.1, and are presented in Figure 8.1. Although different discount rates were used in the literature to differentiate the technologies depending on their perceived risks, an invariable 5% discount rate is applied to the levelised cost estimates of the generating sources herein, given the comparative nature of the

assessment, and given that 5% has been assumed in several sources for costing energy generating sources, particularly the NEA *et al.*, (2005) publication.

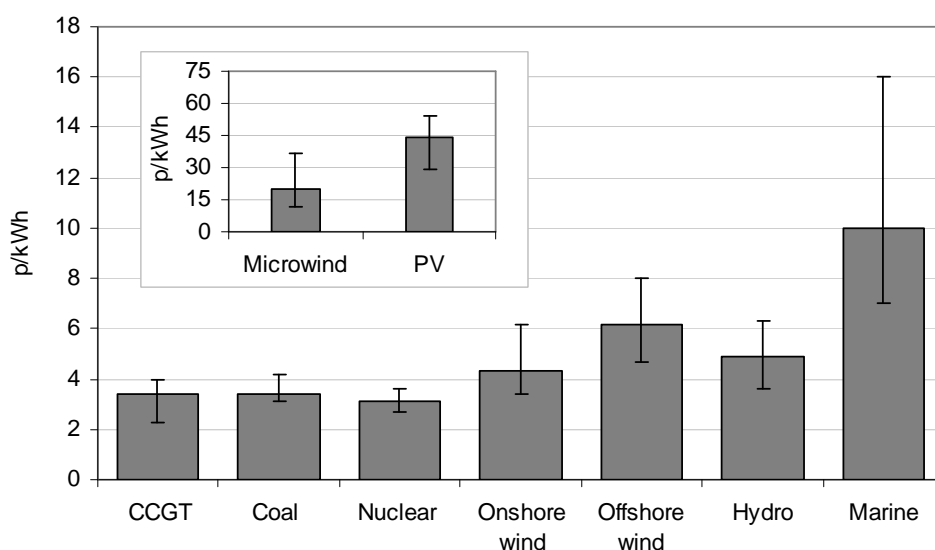


Figure 8-1 Levelised costs of various large and small scale, conventional and renewable electricity generating sources (p/kWh)

Figure 8.1 demonstrates that conventional supply sources (i.e., CCGT, coal, and nuclear) remain substantially more cost-effective in delivering a kWh of electricity than renewable ones, particularly when compared to the assessed microgenerators (microwind and PV).

However, although the costs of electricity produced by the centralised generation plants are in the area of 2 - 4 p/kWh, by the time this electricity reaches the domestic end user it would have increased to between 4 - 10 p/kWh, 'driven primarily by the added cost of network transportation and distribution services' (Strbac *et al.*, 2007). A slight relative improvement in the economics of microgenerators follows, given that the latter systems do not use either the transmission lines, or the high voltage distribution lines. They will use the low voltage network, particularly when exporting electricity. Furthermore, if environmental damages are internalised, the difference in levelised cost between the renewable energy systems (including the two shown microgenerators in Figure 8.1) and the conventional ones would reduce. Figure 8.2 illustrates this matter, keeping the cost of passing through the lower voltage distribution line constant for all technologies, however adding (1) 4 p/kWh to the levelised costs of conventional fossil-fuel and nuclear sources for transmission and higher and medium voltage distribution costs, adding (2) 2 p/kWh to the large-scale renewable sources given their connection to high voltage distribution lines, and (3) integrating the cost of carbon emissions using the mean SCC estimated in Chapter 3.3.1. The 100-yr GWP from the IPCC of manufacturing and use of the generating sources, at plant gate, have also been estimated from Simapro V7.1 LCA software using the ecoinvent 2.1 database.

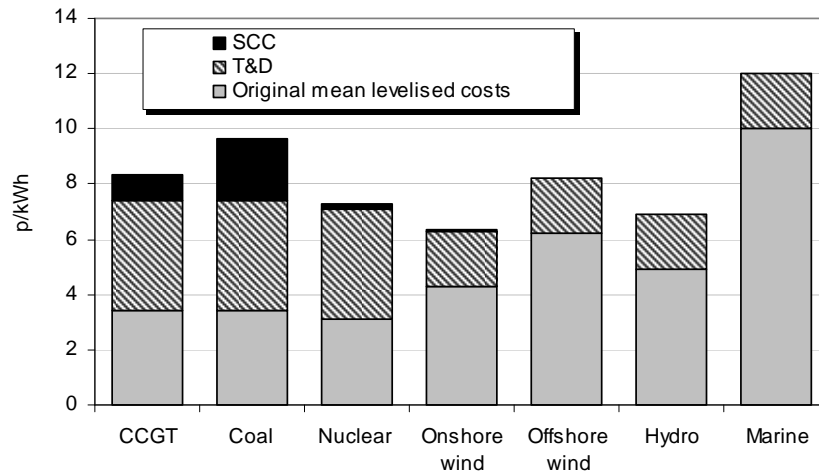


Figure 8-2 Mean levelised cost with T&D (high voltage only) & mean SCC

Centralised renewable energy sources, particularly onshore and offshore wind and hydro, are now relatively more favourable when compared to conventional natural gas and coal. Comparing these levelised costs of Figure 8.2 with the microgenerators in Figure 8.1, it is obvious that microwind can compete if installed in an area characterized by a strong wind resource. PV on the other hand remains uncompetitive in the UK.

With respect to heating energy sources, Figure 8.3 presents the levelised cost (in p/kWh_{th}) of several hot water generating options (including the assessed SHW system in this thesis). Similar to the electricity delivering microgenerators, the SHW system is currently an uncompetitive option for generating energy in the form of hot water.

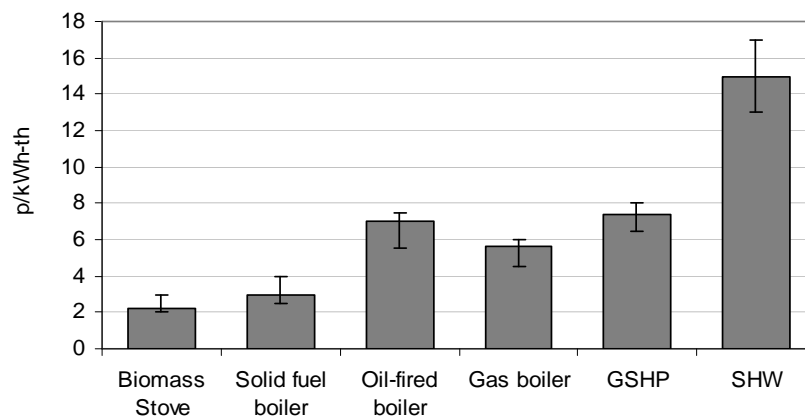


Figure 8-3 Summary of levelised costs of heat and hot water generating sources

If CO_{2e} are internalised through a similar approach as above (i.e., combining mean social cost of carbon with CO_{2e} of production per kWh), the economics will improve slightly, yet not enough to make any substantial difference, as shown in Figure 8.4.

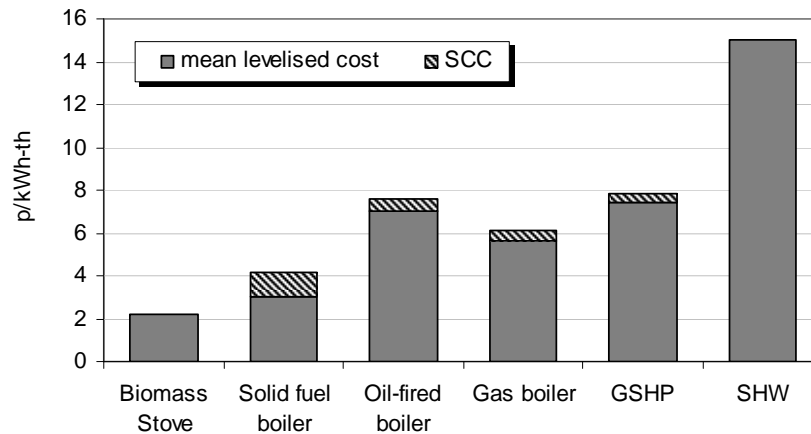


Figure 8-4 Summary of levelised costs of heat and hot water generating sources with SCC

The addition of the SCC in Figures 8.2 and 8.4 should be taken as tentative only, given that they rely on selected default systems in the SimaPro software database (with the exception of the assessed microgenerators in this study), and therefore other selected systems would undoubtedly yield different results. Part of the future research by the renewal of Supergen, i.e., the “Highly Distributed Energy Future (HiDEF)” will be involved in assessing, first hand, the life-cycle implications of further heat and electricity generating sources.

The range of levelised costs for the various energy generating sources calculated above are bound to change in the future however, particularly as the capital costs of these systems change relative to one another (see Chapter 7), and as running costs also tend to change significantly and in unexpected ways as demonstrated in the 2007-2008 oil price hikes.

Overall, the assessed microgenerators still have a long way to go in order to compete with centralised energy systems. They are currently the least cost-effective means of producing either electricity or hot water. On these relative economic terms, even after internalised additional network impacts and carbon emissions, the assessed microgenerators should not be given the go-ahead, with the exception of microwind in a high-wind resource setting.

The CEA showed particularly that solar driven systems are very expensive in the UK relative to other options. The reasons for this are mainly due to the fact that the UK does not have a rich solar resource, and due to the relatively expensive costs of PV in the UK when compared to other countries.

The levelised cost for PV in the UK was estimated to be 34-52 p/kWh according to Allen *et al.* (2008a), similar to the range indicated for the various possible input values of 1kWp PV system in the UK presented in Figure 8.1 above. In a solar-rich country like Lebanon, for example, which is located in the Middle East and receives almost twice as much solar irradiance as the UK, the levelised cost for a PV system was estimated to range from \$c10-16/kWh only (El-Fadel *et al.* 2009, reproduced in Appendix 8).

Furthermore, it seems the UK's PV costs are on the higher end of the available range if an international comparison is performed. Figure 8.5 makes such a comparison of grid-connect system prices in Euros (2008), and it clearly indicates that the UK's PV prices are among the highest in Europe, with the exception of Norway and Sweden (IEA PVSP, 2009).

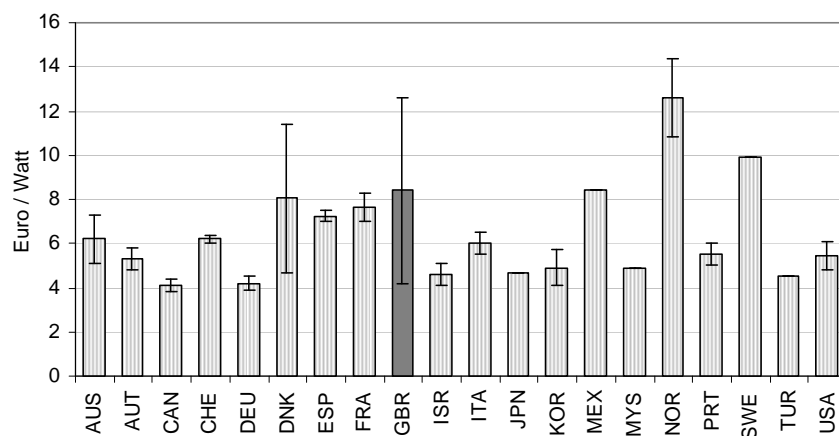


Figure 8-5 Indicative installed system prices in selected countries
(Source: IEA PVSP, 2009)

Figure 8.5 indicates further that there is a large variation of prices between the PV systems in the UK itself. This fact was validated by an indication that the UK PV industry is 'uncompetitive' (Jardine & Bergman, 2009).

Therefore it can be concluded that microwind can play an important albeit small role in assisting in the implementation of the 'lead scenario' (30% of electricity from renewables by 2020) of the UK Renewable Energy Strategy. However, the solar-driven assessed microgenerators, particularly SHW and PV/BIPV, are the most expensive technologies for delivering either heat or electricity, and therefore there could be an argument against supporting these systems in the UK. This argument can go a step further in advising the UK to 'free-ride', particularly with solar PV, until the learning effect, induced by the deployment of solar PV in other, more solar-intensive countries, substantially reduces the costs of PV (through the reduction of PV panel costs). A positive economic outlook can be achieved by around the years 2016-2018, as indicated to in Chapter 7.4.2.1 and Figure 7.5. This argument however excludes the fact that a small part of the learning effect can only be achieved from increased local installation and learning, as mentioned earlier in Chapter 7.4.2.3.

Counter-arguments that aim to encourage the UK government to support the assessed microgenerators, including the solar-driven technologies, would need to assess the importance of other attributes discussed in Chapter 7. These other attributes, besides costs and environmental impacts, are taken into account in the next section.

8.1.3 Multi-attribute rating of generating sources

Given the ‘integrated nature’ of this thesis, and the practical benefits of coming out with some kind of recommendation as to whether or not to support the assessed microgenerators (as important technologies to assist in fulfilling the UK Renewable Energy Strategy goal of 30% and 12% of electricity and heat, respectively, to be secured from renewables), a straightforward exercise involving a simple multi-attribute rating technique (SMART) is applied. The exercise targets the assessed microgenerators in relation to other generating sources, following the process advocated by Goodwin & Wright (2009), and includes many of the possible important attributes of energy generating systems, both quantitative and qualitative ones, discussed through this thesis.

SMART consists of seven stages (Goodwin and Wright, 2009);

- *Identify the alternative courses of action;*
- *Identify the attributes that are relevant to the decision problem;*
- *For each attribute, assign values to measure the performance of the alternative on that attribute;*
- *Determine a weight for each attribute;*
- *For each alternative, take a weighted average of the values assigned to that alternative;*
- *Make a provisional decision;*
- *Perform sensitivity analysis*

SMART is performed on the electricity and heat generating sources, separately. It is applied here more to show that there can be an alternative decision-aiding tool which can systematically structure the subjectivity of the CBA qualitative attributes, then it is to actually decide whether or not the microgenerators should be advocated and supported.

Seven electricity technologies are selected for comparison; two microgenerators being PV and microwind, two large scale renewable sources being large onshore wind farms and hydro schemes, and three conventional sources of energy being nuclear, coal, and natural gas. For the heat-generating sources, all the five technologies presented in Figures 8.3 and 8.4 are selected (i.e., biomass stove, solid fuel boiler, oil and gas-fired boilers, GSHP, and SHW). These are the alternative courses of action (or technologies) to be assessed, respectively, through SMART.

The identification of the attributes relevant to these technologies is required next. There are many possible indicators that can be used to characterize the energy sources. For example, the NEEDS projects implemented a multicriteria evaluation (MCE) using ‘energy resource’ (MJ), ‘mineral resources’ (ores), ‘climate change’ (CO_{2e}), and ‘biodiversity impacts’ (PDF/m²/kWh per annum) among other indicators for environmental criteria, while ‘average generation costs’ (p/kWh), ‘employment’ (person-years/GWh), and ‘independence from foreign energy sources’ (ordinal scale) for the economic dimension, among others indicators for reliability and social and individual risks (NEEDS, 2008b).

For the assessment here, many of the criteria mentioned in the CBA, both in the quantitative analysis and the qualitative ones, would be used as attributes, as would some attributes be adopted from the NEEDS project on MCE of alternative energy sources. These are shown in Figure 8.6.

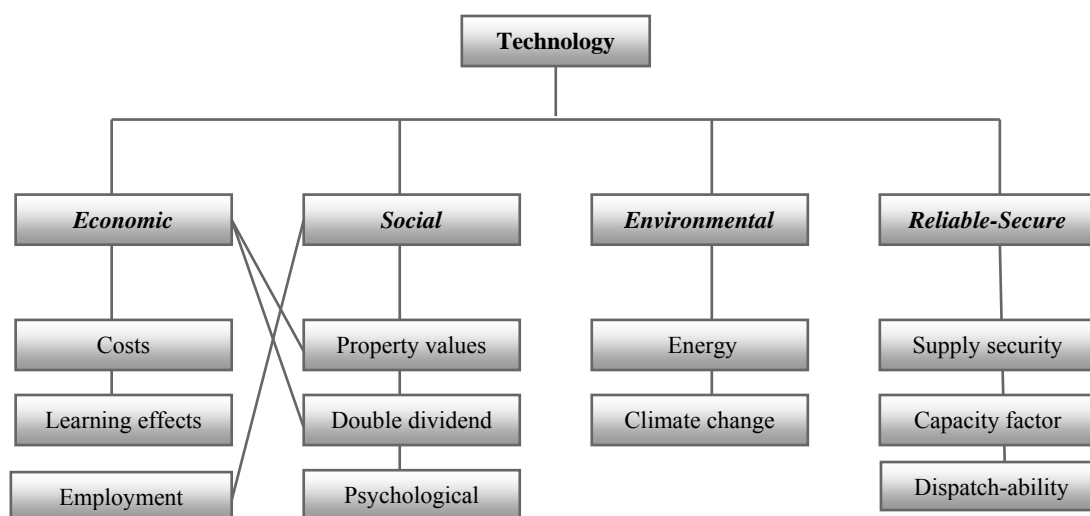


Figure 8-6 Value tree for energy generating sources

Economic attributes are broken down into costs, specifically levelised costs (p/kWh) obtained from the CEA section earlier, and the potential future prospects of costs. The social dimension has three attributes; being the impact of property values from energy generating sources, for example, PV (or by proxy SHW and GSHP systems) may induce increases in property values as mentioned in Chapter 6, while a coal-fired plant may induce reductions in house property values within its vicinity, double dividend effects, and psychological implications (employment may also be placed under the social umbrella, just as property values and double dividend can be under the economic criteria). The environment dimension contains ‘resources’ in the form of ‘energy intensity’, and ‘climate change’ implications in the form of ‘carbon dioxide equivalents’ (CO_{2e}).

Reliability of supply are added for comprehensiveness, and it is measured through (1) supply security measured through the extent of independence from foreign energy resources, (2) capacity factor (for electricity generating sources), and (3) flexibility of dispatch, measured via an ordinal scale from the NEEDS (2008b and 2009b) project MCE reports. The latter gives an indication of how reliable an energy source is to deliver its energy when needed.

It is important that the attributes selected for SMART have ‘mutual preference independence’, in other words the attributes must not be related to one another (Goodwin and Wright, 2009). Yet some of the attributes may relate to one another, such as ‘energy’ and ‘climate change’, and ‘capacity factor’ and ‘flexibility of dispatch’. However, given that (1) these indicators really measure different things, although they tend to be correlated (i.e., if one technology has a high capacity factor, chances are it will have higher flexibility of dispatch, with some exceptions such as nuclear power), (2) given that there are two correlated pairs of attributes listed above

which favour conventional plant and two others which favour renewables, and (3) given that these correlated attributes were all used in the multicriteria sustainability appraisal of energy generating sources by the NEEDS project, they will be used together here in the SMART.

Some of the above attributes are easily assigned precise values, while others cannot avoid some subjectivity. In fact, 7 of the 10 attributes for the electricity-supply can be calculated with confidence from estimated parameters, while the remaining three are author-weighted through ordinal scales. Table 8.2 presents the values of the selected attributes for these electricity-supply sources, and the methodology or literature source(s) used to obtain those values.

Attribute	Unit	Source	PV	u-wind	Large wind	Hydro	nuclear	coal	N. gas
Cost	p/kWh	Adopted from CEA	44	20	5	5	3	3	3
Learning	%	Several Literature	18	20	10	10	5	5	5
Employment	Person yr/GWh	NEEDS, 2008b	150	150*	50	50*	50	50	100
Property value	Ordinal ranking	Author	100	50	40	40	0	20	30
Double dividend	Ordinal ranking	Author	100	50	0	0	0	0	0
Psychological	Ordinal ranking	Author	100	50	25	25	0	10	20
Energy	MJ/kWh	Allen <i>et al.</i> , 2008c	1.66	0.38	4.06	3.83	12.7	15.7	8.32
Climate change	CO _{2e} /kWh	LCA author	0.11	0.022	0.0116	0.00335	0.00793	1.07	0.484
Security of supply	Ordinal ranking	NEEDS, 2008b	100	100	100	100	40 ⁴⁰	80	50
Capacity factor	%	Several Literature	12	20	30	40	85	90	85
Flexibility of dispatch	Ordinal ranking	NEEDS, 2008b	20	20*	30	50*	60	80	100

* Calculated by author

Table 8.2 Values for the attributes for electricity-supply generators

The author-weighted ordinal scales in Table 8.2 are already referenced relative to 100 and 0, meaning 100 represents the best case and 0 the worst case. For example, PV has the most positive effect, potentially, on property values, through the discussion in Chapter 6. Microwind has been given half the values of PV for ‘property value’,

⁴⁰ “The UK currently has 19 nuclear reactors in operation, providing about one fifth of its electricity. The combined power of all of these reactors is 10,982 MWe so the UK may have enough uranium in their stockpiles to supply about 27% of what is needed over the next sixty years. That still leaves a large gap of 73% in supply that needs to be filled, and this will require the buying of more uranium or the acquisition of uranium mining companies to fill the supply gap” (Uranium Stocks, located at; <http://www.uranium-stocks.net/>, accessed Tuesday, 06 October 2009)

‘double dividend’, and ‘psychological’ impacts because of some uncertainties involved, precisely that microwind may also cause noise (which then may lower housing value and cause some psychological stress) and is less predictable than PV (therefore potentially lowering the double dividend effect). Conventional power plants are likely to have negative effects on housing prices within their vicinity. A US study indicated that 3-7% decreases in housing values and rents occur within two miles of power plants with somewhat larger decreases within one mile and for large capacity plants (Davis, 2009). Nuclear is given the worst value or zero in this study (author-weighted), followed by coal and natural gas. Double-dividend can induce a reduction in energy use for PV owners (if coupled with smart meters, as discussed also in Chapter 7), however no such effects can be assumed for far away conventional plants, and it is uncertain whether microwind may induce energy reduction. Positive psychological impacts are attributed to PV mostly, followed by microwind, while being located next to a nuclear plant may have negative psychological implications on people in the area, although this claim is not substantiated by the literature. The heat-generating sources are valued in Table 8.3.

Attribute	Unit	Source	Biomass	Coal	Oil	N.Gas	GSHP	SHW
Cost	p/kWh	Adopted from CEA	2.2	3	7	5.6	7.4	15
Learning	%	Several Literature	15	0	0	0	50	50
Employment	Person yr/GWh	NEEDS, 2008b	-	-	-	-	-	-
Property value	Ordinal ranking	Author	75	0	25	50	100	80
Double dividend	Ordinal ranking	Author	-	-	-	-	-	-
Psychological	Ordinal ranking	Author	75	0	25	50	80	100
Energy	MJ/kWh	Allen et al., 2008c	5.37	7.38	5.1	4.4	3.61	0.51
Climate change	CO _{2e} /kWh	LCA author	0.0117	0.59	0.321	0.278	0.143	0.023
Security of supply	Ordinal ranking	NEEDS, 2008b	80	80	0	40	90	100
Capacity factor	%	Several Literature	-	-	-	-	-	-
Flexibility of dispatch	Ordinal ranking	Author	60	70	80	100	80	20

Table 8.3 Values for the attributes for heat (and hot water) generators⁴¹

All the other values in Tables 8.2 and 8.3 that did not have an ordinal scale with a worst case equal to zero and best case equal to 100 would have to be normalised to

⁴¹ Accurate data on employment impacts were unavailable on all the indicated heat-generating systems of Table 8.3. Furthermore, there double-dividend impact are for electricity generating sources only, although future research on the impact of heat and hot water use from installing a renewable energy system is warranted. Furthermore, capacity factor is commonly used term for electricity-supplying systems as opposed to heat supplying.

100 in order to make them usable for the SMART analysis. This is simply done through the equation 8.2 (Goodwin & Wright).

$$\frac{100 * (-\text{Observed value} + \text{worse value})}{(-\text{Best value} + \text{worst value})} \quad 8-2$$

The normalised values for the electricity-generating sources and the heat generating sources are presented in the upper and lower sections of Table 8.4, respectively.

Electricity generating sources							
Attributes	PV	u-wind	Large wind	Hydro	nuclear	coal	Natural gas
Cost	0	58.5	95	95	100	100	100
Learning	86.6	100	33.3	33.3	0	0	0
Employment	100	100	0	0	0	0	50
Property value	100	50	40	40	0	20	30
Double dividend	100	50	0	0	0	0	0
Psychological	100	50	25	25	0	10	20
Energy	90	97	99	100	0	0	34.4
Climate change	90	98	99	100	99	0	55
Security of supply	100	100	100	100	40	80	50
Capacity factor	0	10	20	32	83	100	83
Flexibility of dispatch	20	20	30	50	60	80	100

Heat generating sources							
Attributes	Biomass	Coal	Oil	N.Gas	GSHP	SHW	
Cost	100	94	63	74	60	0	
Learning	100	0	0	0	50	50	
Employment	-	-	-	-	-	-	
Property value	75	0	25	50	100	80	
Double dividend	-	-	-	-	-	-	
Psychological	75	0	25	50	80	100	
Energy	29	0	33	43	55	100	
Climate change	100	0	47	54	77	98	
Security of supply	80	80	0	50	80	100	
Capacity factor	-	-	-	-	-	-	
Flexibility of dispatch	60	70	80	100	80	20	

Table 8.4 Normalised values of the attributes

The weighting or relative importance of each attribute is required next. This is done through what Goodwin and Wright (2009) refer to as ‘swing weights’. The decision-maker is requested to imagine a hypothetical case where all the attributes above are at their least preferred levels first, yet then the following question is put forward; ‘if one of these attributes can be moved to its next best level, which would he or she choose?’ (Goodwin & Wright, 2009). This question is repeated to the next preferred attribute that the decision-maker would want to move to its respective best level, and so forth, until a ranking of all the attributes is completed.

The first attribute selected is given a ranking weight of 100, while the other attributes are weighted through asking the decision maker how important is a swing from each

of the other attributes' 'worst cases' to their respective 'best cases' in relation to the best first case (Goodwin & Wright, 2009).

For the analysis here, 'cost' is assumed to be the most important attribute which is considered with respect to generating sources. This assumption is made given that 'cost' is the main barrier to the uptake of assessed micro-generators, responsible for the poor NPV results obtained throughout this thesis.

A sensitivity analysis is performed through involving other opinions (i.e., other than the author) on the weighting of the attributes. A questionnaire sent to the Sustainable Energy Research Team (SERT), reproduced in Appendix 6, to complete the ranking of the attributes outlined in Figure 8.6, and augments the author's own ranking to increase the credibility of the analysis. Four respondents' (five with the author) answers to the weighting of the above used attributes are presented in Table 8.5.

Attributes	Author	Respondent			
		A	B	C	D
Cost	100	100	100	100	100
Learning	30	40	50	50	30
Employment	35	25	25	40	70
Property value	25	60	40	15	0
Double dividend	15	40	55	45	10
Psychological	20	25	30	40	20
Energy	50	75	60	60	70
Climate change	75	80	70	80	90
Security of supply	40	50	45	70	80
Capacity factor	60	70	50	50	60
Flexibility of dispatch	75	70	70	60	50

Table 8.5 Respondent's weighting values for the selected attributes

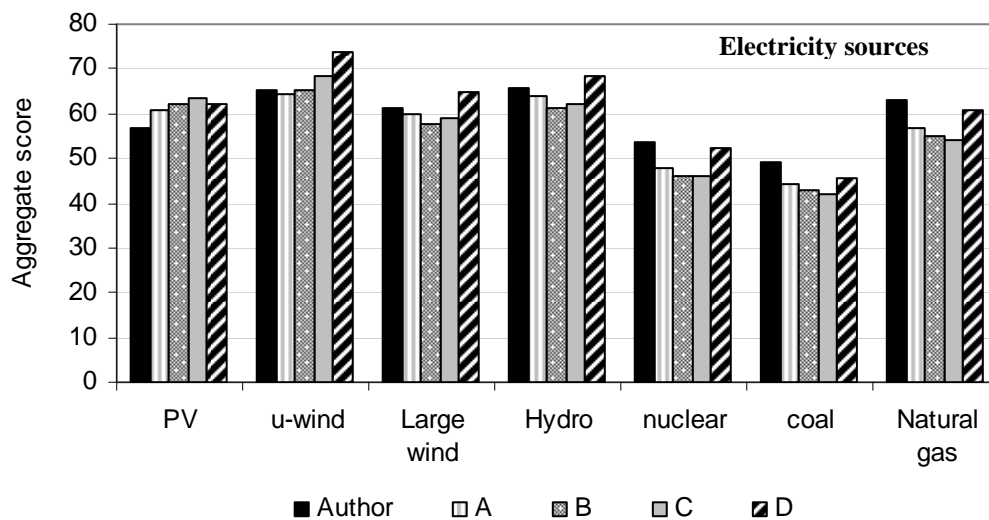
Similarly, the respondent's weighting of the attributes is normalized so that they add up to 100, simply by dividing each weight given for each attribute by the sum of the weights and multiplying by 100 (Goodwin & Wright, 2009). This is done for both the electricity and heat-generating sources in the upper and lower parts of Table 8.6, respectively.

Electricity generating sources					
Attributes	Author	Respondent			
		A	B	C	D
Cost	19	16	17	16	17
Learning	6	6	8	8	5
Employment	7	4	4	7	12
Property value	5	9	7	2	0
Double dividend	3	6	9	7	2
Psychological	4	4	5	7	3
Energy	10	12	10	10	12
Climate change	14	13	12	13	16
Security of supply	8	8	8	11	14
Capacity factor	11	11	8	8	10
Flexibility of dispatch	14	11	12	10	9

Heat generating sources					
(%)	Respondent				
Attributes	Author	A	B	C	D
Cost	24	20	22	21	23
Learning	7	8	11	11	7
Property value	6	12	9	3	0
Psychological	5	5	6	8	5
Energy	12	15	13	13	16
Climate change	18	16	15	17	20
Security of supply	10	10	10	15	18
Flexibility of dispatch	18	14	15	13	11

Table 8.6 Respondent's weighting values normalized for the selected attributes for all generating sources

Given the normalized weights for each attribute given by the four respondent plus the author, the value of each technology can now be obtained by simply using an additive model, meaning that each value of the attributes is multiplied by the weight attached to that attribute; and the resulting products are then summed and divided by 100 to obtain the overall value of benefits for each generating source (Goodwin & Wright, 2009). The results of this SMART exercise are shown in Figure 8.7 for each respondent's answer and for both the electricity generating source (upper figure) and the heat generating source (lower figure).



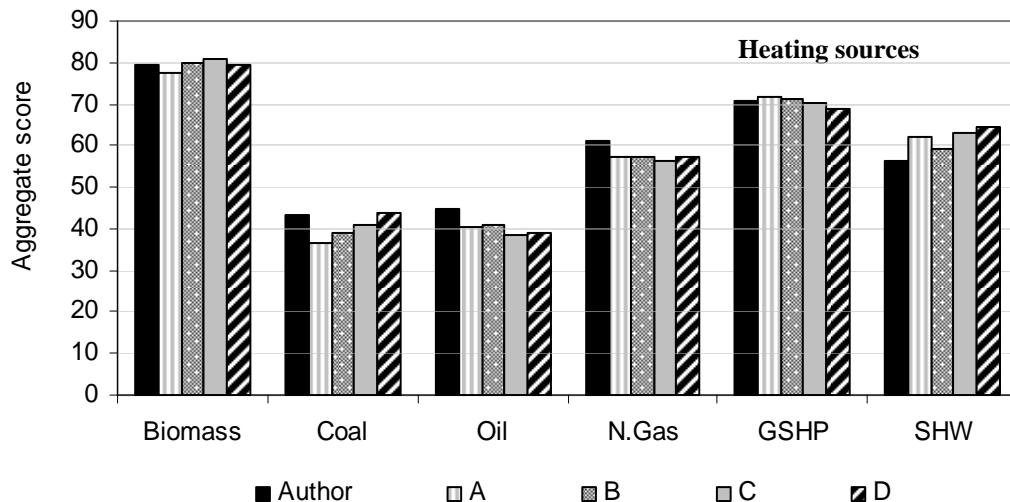


Figure 8-7 SMART results

Although different respondents' weighting of the attributes has, as expected, led to different ranking results for all the energy generating sources, there are obvious winners for the heating technologies, being biomass coming first, followed by GSHP. SHW systems are ranked 3rd by four respondents, except the author whom ranked natural gas boilers better than SHW systems.

For the electricity generators, coal-fired plants came last, following by the second worst category going to nuclear. Four of the five respondents' scores put microwind ahead of the rest, while one respondent placed microwind second. PV was scored second by 2 respondents, while the remaining 3 respondents scored PV third, fourth and fifths, respectively.

These SMART results indicate that other attributes, not monetized in the CBA or the CEA, can play an important role in the decision to lend support (or decline) to the assessed microgenerators. For while cost is the most important attribute characterizing the relative advantage or disadvantage of energy sources, other attributes such as concerns stemming from climate change, security of energy (including the benefits of diversifying energy supply, as mentioned in Chapter 7), and the promotion of employment (for example) remain important parameters to consider. These attributes are part of the UK Renewable Energy Strategy, and part of what Lipp (2007) described as reasons for deploying renewable energy systems (see Chapter 6.4.2). The SMART analysis recommends the investment in PV, microwind, and SHW, given that other technologies which currently populate the UK energy sector, such as coal-fired plants for electricity and coal and oil boilers for hot water, have scored lower than the assessed microgenerators, on aggregate.

8.1.3.1 Limitations and discussion of SMART

The SMART analysis is really a subjective exercise in the end, and results will change considerably, depending on which attributes are selected, how these attributes are measured themselves, and what weights are given to those attributes in relation to one another.

However, it is precisely because problems are complex and involve either the assessment of an alternative or a comparison of different alternatives that have quite different characteristics and/or quantitatively and qualitatively measurable attributes together, that such tools as multicriteria evaluation (MCE) are called for. This is what has been applied by one of the deliverables of the NEEDS project. The results from the NEEDS project's more complex MCE, for example, showed that *“solar PV technologies and solar thermal technology, are consistently preferred by a majority of stakeholders with only a few outliers”* (NEEDS, 2009b).

The SMART exercise performed above is more to show that there is an alternative methodology that can be used on the assessed microgenerators, which can structure and systematically organise the subjectivity involved in deciding how important the qualitative attributes of the assessed systems are. However, the results would undoubtedly reflect the views of the stakeholder asked. In the SMART exercise above, it was the Sustainable Energy Research Team (SERT) at the University of Bath which were asked to rank and weigh the attributes. Therefore an inherent bias towards 'sustainable' attributes could be present. Had this study's main objective been to perform a MCE, then tens to hundreds of stakeholders would have been consulted, as in the NEEDS project.

Nevertheless, all the tools used in this study form an 'integral appraisal toolkit', which are, again, decision-aiding tools as opposed to decision making. To this end, the decision to install or not to install, to support the installations or not to support the installations, of the assessed microgenerators, are for the actual individuals and/or governments to decide. The proposed financial support tariffs discussed in Chapter 6 may already give a hint as to what the government has decided to do with respect to the assessed systems. This decision could not have been based on the quantitative part of the CBA alone.

8.1.4 Cost-benefit analysis of an onshore wind farm

A CBA of a UK onshore wind farm is implemented to better illustrate the economies of scale that is found with renewable energy technologies, particularly the comparison of the assessed 600W microwind system with the economics of a larger wind infrastructure, analyzed on a per kW basis. Environmental approach 1 is selected for the analysis to simplify the results and provide a conservative estimate for the CBA.

The same capital cost, operating and maintenance (O&M) costs, and energy output range is assumed as in Table 8.1 in Chapter 8.1.2. Additionally and as discussed in the CEA of Chapter 8.1.2, a 2 p/kWh is added to costs to account for network fees.

The CO_{2e} emissions from the life-cycle manufacturing and installing of a wind turbine will depend again on the wind turbines' size, type, the place of purchase and the scale of the wind farm in its entirety. I.e., a 100 MW wind farm will have different life-cycle emissions in production and installation than a 10 MW wind farm. For our purposes here, the CO_{2e} emissions are obtained from literature, particularly from Schleisner (2000).

Schleisner (2000) has indicated that the life-cycle CO_{2e} emissions of a 9 MW wind farm amounted to 3838 tons. These emissions are deducted from the life-cycle CO_{2e}

emissions saved due to the operation of the wind farm displacing UK grid electricity which has a CO_{2e} factor of 0.697 kg of CO_{2e} per kWh (see Chapter 4.3.2) and monetized through the same social cost of carbon (SCC) adopted in this thesis (see Chapter 3.3.1 and Table 3.10).

Figure 8.8 indicates the NPV and the benefit-cost ratio of a UK onshore wind farm on a kW basis and using a 5% discount rate as in the CEA.

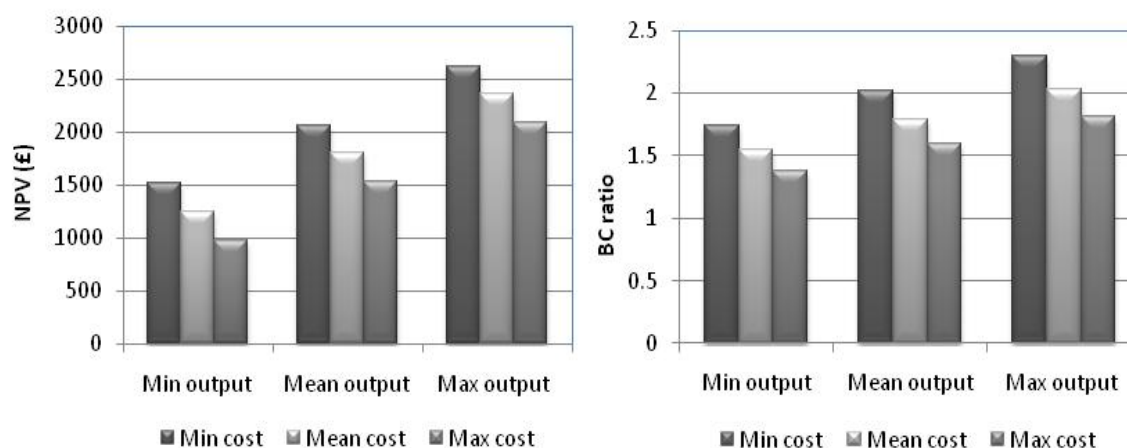


Figure 8-8 NPV and BC ratio of an onshore wind farm (on a kW basis)

Figure 8.8 is a conservative representation of the NPV and BC ratio for onshore wind farms in the UK. This is the case given (1) the displaced price of electricity has been adopted for the analysis as opposed to the value of electricity (i.e., 12 p/kWh as opposed to 16.3 p/kWh), (2) a relatively small (9 MW) wind farm has been analyzed, and (3) only environmental approach 1 which accounts for CO_{2e} emissions has been utilised (other approaches with the exception of the EI-99 that cover more environmental impacts would of yielded a yet more positive outlook).

The CBA of the onshore wind farm clearly shows the benefits of going large scale with BC ratios for the mean capital cost cases ranging from 1.5 to 2, depending on energy output. It is no surprise that wind energy constitutes one of the main growing sources of green energy in the UK and the world. Over the past ten years, the Global Wind Energy Council has estimated that global wind power capacity has grown at an average cumulative rate of over 30%.⁴²

8.2 Discussion and concluding remarks

There are many attributes that should be taken into account when considering energy generating sources. Most of these attributes were included, one way or another, through the use of the various ‘integrated appraisal’ tools in this thesis, such as CBA, LCA, financial appraisal, CEA and SMART. The benefits of using CEA and SMART, as implemented in this chapter, is to place the assessed microgenerators in the context of or in relation to other generating sources.

⁴² See Global Wind Energy Council on <http://www.gwec.net>.

The assessed microgenerators have been shown to be the more costly energy generating sources in the UK. The levelised cost of conventional electricity-supplying sources, such as coal, natural gas, and nuclear, amounted to around 2-4 p/kWh at plant busbar and 4-10 p/kWh at the domestic end-user level. The levelised cost for the microgenerators amounted to 27-65 p/kWh for the PV and 12-37 p/kWh for the microwind. The SHW system had a levelised cost of 13-17 p/kWh_{th}, whereas the most widely used heating source, natural gas boilers, had a levelised cost of 4.5-6.5 p/kWh_{th}. Even when GHG emissions are internalised in the CEA, as done also through environmental quantification of approach 1 (used in the CBA), there remained a significant difference between the economic costs of the assessed microgenerators and other more conventional sources of energy. The only exception was microwind, which could compete with alternative energy sources if installed properly. Given that there always will be budget constraints in any decision-making process, including the allocation of government revenues and/or household incomes, opting for the alternative which would yield the desired outcome in the most cost-effective way is an economic principle which is hard to circumvent. For these reasons, the deployment of the assessed solar-driven energy sources will remain constrained by their excessive costs in relation to other energy generating sources in the UK. The alleviation of this barrier, through the introduction of FITs for the electricity microgenerators, and the awaited introduction of Renewable Heat Initiative (RHI) for the SHW system, could go some way in levelling the competition between large-scale conventional and small-scale micro-generating energy sources. Furthermore, this proposed level of support gives a strong indication that other attributes, besides costs, are being considered as important drivers of policy. These attributes or objectives include, as aforementioned through the UK Renewable Energy Strategy, the need to reduce GHGs, increase energy security of supply, and 'create new opportunities for individuals, communities and business to harness renewable energy' (DECC, 2009i).

Furthermore, microgenerators in the UK fit better into the characteristics or the requirements behind a 'sustainable energy system'. Recall from Chapter 1, Mitchell (2008) indicated that a sustainable energy system is characterised by the following;

'A sustainable energy system is characterized by publicly aware citizens that see the connections between energy and the environment and who use energy efficiently. Within this system, the environment plays a greater role and is an important driver of policy, while energy security concerns are answered through the diversification of generation technologies, including large-scale and distributed renewables sources, the reduction in dependence on imported oil, and targeting demand reductions through behaviour change or energy efficiency measures. The sustainable energy system will contain different technologies and sizes, connected to both the transmission and the distribution networks which become in themselves 'active'...

One of the main benefits of the assessed microgenerators would be to involve, directly, the UK domestic householder in the process of generating electricity and/or heat. In doing so, coupled with smart metering for the electricity-generating sources, the householder may play a more important role in monitoring his/her energy consumption and energy production, and may be able to reduce the overall demand for imported electricity (or energy for heating water).

Therefore the attributes discussed through the SMART analysis, particularly those presented in Figure 8.6 above, play an important role in the decision as to whether or not to advocate the assessed microgenerators, particularly in light of the objective or path of moving the energy sector towards a more 'sustainable energy system'.

In conclusion, although the assessed microgenerators, particularly the solar-driven ones, still have some way to go before being able to compete with more conventional sources of energy, the internalisation of environmental impacts, the need to ensure an adequate security of supply (reducing the amount of fuels imported and diversifying the UK energy portfolio), the benefits from learning effects due to installation, and the added local benefits in terms of employment, local empowerment, and self-sufficiency, make them valuable alternatives to consider.

9 Synthesis, Conclusions and Recommendations

9.1 Introduction

In this thesis, three assessed microgenerators; specifically a 600W microwind system, 2.1 kWp PV and BIPV systems, and a 2.8m² SHW system have been analysed through an ‘integrated toolkit’ in order to assess their respective performance in the current UK context. A CBA based on outputs and results from energy analysis and LCA has been performed, along with other tools such as financial appraisal, CEA and SMART in order to assess how these systems perform on an individual level and when compared to other energy technologies, respectively.

9.2 Main contributions of this thesis

The main contribution of this thesis was to apply a detailed CBA and financial appraisal on selected microgenerators. The CBA was a society-wide perspective on the performance of these systems, while the financial appraisal took an individual perspective. The approach adopted was innovative, in that the CBA was tailored to the outputs and results from other ‘integrated appraisal’ tools, specifically energy analysis and LCA. To this end, the study could be described as inter-disciplinary.

Within the main contribution of the thesis, the accounting for the value of electricity and hot water and the valuing of the environmental impacts of producing and operating the selected microgenerators had to be performed.

With respect to the eliciting of the ‘value’ of electricity and hot water, this was a departure from the convention of using the displaced energy revenues as proxy for value of that energy, used in most of the literature encountered on the economics of renewable energy. The use of actual ‘value’ from constructed demand curves was thought to yield more reliable estimates given that it is the revenue added to the consumer surplus which measures the total willingness-to-pay (WTP) for either electricity or hot water.

In parallel, the study made extensive use of LCA outputs and results, and influenced (or pushed for) in return the use of other LCIA methods which were thought to be more compatible (or used with less controversy) with CBA. Four alternative approaches were established. Two of the approaches focused on the LCA inventory, specifically analysing the impact of carbon emissions (approach 1), or the impact of other important airborne pollutants in addition to carbon (approach 2). The other two approaches used LCIA methods that were more suited with CBA than the use of the Eco-indicator 95, the main LCIA method used by Allen *et al.* (2008a, 2008c and 2009) and Hammond *et al.* (2009). Specifically, the use of the Eco-indicator 99 and the EPS 2000 was thought to be more attuned with the requirements of CBA as they are considered end-point LCIA methods. The inclusion of four approaches in the calculation of the environmental impacts of the selected microgenerators is thought to give more credibility to the analysis, particularly as the uncertainty of quantifying and monetizing environmental impacts are considered, generally, significant (e.g. through the use of 3-4 standard deviations in the mean damage values for the air pollutants themselves).

The qualitative part of the CBA (Chapter 7) contributed to the comprehensiveness of the analysis with respect to how these microgenerators performed in the UK. Two possible parameters were included in the qualitative part, although they were monetized; double dividend effects and positive experience effects. Particularly for the latter parameter, a new method for internalising the positive experience effects of currently installed microgenerators was established or recommended. These parameters have the ability to contribute significantly to the benefits of the assessed systems. They were not included in the quantitative CBA due to the fact that they need further assessment or research (double dividend), or given that the approach adopted was new (positive learning effects), and therefore could not be compared to some reference to gain sufficient confidence in the credibility of the approach. Other important qualitative parameters, such as effects on employment, local self-reliance and psychology were also addressed, with the aim of making the analysis as thorough as possible.

The financial appraisal applied in this study contributed to the understanding of how these microgenerators fared on the individual or household level, with and without government support. The financial appraisal complimented the CBA, and could be said to exemplify the feasibility aspects of the microgenerators. In other words, the understanding of how much these systems cost, their respective benefits, and how the current and proposed government support mechanisms changed these system's performances on the household level, is considered very important if the objective is to increase the deployment of these technologies. This study has contributed sufficiently towards understanding the performances of these systems - financially.

The second main contribution of the thesis was to enhance the applicability of the 'integrated appraisal' methodology. Although the rationale or motive of the 'integrated appraisal' was born from the three dimensions of sustainable development; ecology, economy, and society, the applicability of these three dimensions into one integrated framework which would assist in the decision-making process was a challenge, particularly for the CBA. Energy analysis is, in part, a LCA on energy inputs and outputs, and therefore the compatibility of these two tools is quite high, and together they produce relatively clear results with respect to the performance of the microgenerators in terms of energy, for example, such as through the energy gain ratio (EGR) indicator, and can give a clear indication as to whether or not the environmental implications of installing the systems yield net environmental benefits across the impact categories (as in Allen *et al.*, 2008a). Integrating LCA and CBA proved more challenging however and involved the establishing of four environmental quantification approaches. The constraints of combining these two tools through these four approaches were discussed and solutions delivered within the CBA. To this end, the study contributed to the integrated appraisal's usefulness as a decision-aiding kit.

The third contribution of this thesis was to apply alternative tools, particularly a CEA and a MCE (specifically SMART), in order to better situate the microgenerators in relation to other possible alternatives of energy sources (CEA), and to make known that alternative means or tools (MCE) to deciding whether or not the microgenerators are worth using within the 'integrated appraisal', particularly as many different attributes, both quantitative and qualitative, some of which could not be monetized in the CBA, would need to be traded-off against one another. They could be however

considered add-ons to the analysis, and would be useful as separate research in and by themselves.

9.3 Synthesis and results of the study

9.3.1 CBA

The primary objective of this study, a CBA of selected microgenerators, relied on the outputs of ‘energy analysis’ and ‘LCA’ to obtain the NPV and BC ratio values, with a secondary objective of enhancing the ‘integrated approach’ methodology.

Outputs of energy analysis fed directly into CBA and LCA, while the links between LCA and CBA proved slightly more complicated, particularly given that these two latter tools have substantially different purposes and perspectives. Chapter 3 presented these differences and difficulties, and presented several possible solutions to better integrate LCA output with CBA. Four approaches for accounting for and monetizing the environmental implications from the manufacturing, production, and use of the selected microgenerators were established.

The first two approaches used relied only on the LCA inventory, or LCI. The first approach, the ‘climate change focused approach’, was characterized with high compatibility with CBA, as GHGs are not site specific.

The second approach, or the ‘airborne pollutant approach’, augmented approach 1 with other important air pollutants, specifically sulphur dioxide, nitrous oxides, and particulate matter. These pollutants are site-specific, and therefore approach 2 suffered from the lack of knowledge as to where and when these above-mentioned emissions (and others presented in Chapter 3) have been released from the manufacture and installation of the selected microgenerators. Given that the microgenerators follow a production or industrial process characterized by a very large number of different small processes (see Chapter 3, Figure 3.6), obtaining such site-specific knowledge would require extensive time and resources. This was not possible for the current study. On the other hand, the assessed damage functions of the ExternE/NEEDS projects were based on the impact pathway approach (IPA) applied on actual emissions from existing large-scale energy generating sources in Europe. Consequently, the emissions, dispersion characteristics, and exposure were all traced, and environmental economic techniques applied (when markets were absent) for the valuation of the exposure’s consequences. However, approach 2 went ahead in combining the ExternE/NEEDS damage function values of the selected airborne pollutants, obtained from the IPA of specific energy sources, with the manufacturing and installation emissions of the assessed microgenerators. This could have been regarded as an inaccurate step until further analysis of this discrepancy, for this study’s specific purposes, showed that the errors could be considered small. Three reasons for this deduction were given.

The first reason is pertained to the electricity-displacing microgenerators only (i.e., excluding SHW systems displacing natural gas or oil). Approach 2 only reduced the quantities of environmental benefits obtained from displacing UK national grid electricity (meaning the use phase of the microgenerators life-cycle) by the same respective quantities of environmental damages caused from manufacturing and

installing those systems. Table 9.1 summarizes these two environmental cost and benefit quantities for the three more important site-sensitive pollutants used by approach 2, along with the consequent percentage of total environmental impacts (both costs and benefits) attributed to the production phase only, assuming the mean energy output estimates for all the systems, respectively.

<i>Total kg</i>	Microwind			PV			BIPV			SHW – elec.		
Pollutant	Prod.	Use.	%	Prod.	Use.	%	Prod.	Use.	%	Prod.	Use.	%
SO ₂	1.4	19	6.8	14.5	65.0	18.2	14.4	65.0	18.1	1.2	37.8	3.1
NO _x	0.7	16	4.2	10.6	51.6	17.0	9.8	51.6	16.0	1.0	30.0	3.2
PM _{2.5}	0.2	1.5	11.8	1.3	5.0	20.6	1.2	5.0	19.4	0.1	3.0	3.3

Table 9.1 Comparing production and use environmental emissions for the 3 assessed microgenerators

Table 9.1 shows that, for example, SO₂ emissions from the production of microwind are about 7% of the total SO₂ emissions estimated in the analysis, the rest pertained to the use side of operating a microwind system. Overall, environmental emissions of the selected airborne pollutants from the manufacturing and installation of the systems accounted for between 3 – 21% of the total environmental emissions. Put another way, between 79-97% of the estimated environmental benefits are accurately accounted for by using the values from the ExternE/NEEDS project, while the remaining could be considered less certain. This relative uncertainty however is reduced when considering other justifications for using approach 2. For example, support for the credibility of approach 2 can be obtained through a study by Krewitt *et al.* (2001), in which it was found that country-specific damage factor for air pollutants derived for specific aggregated sectors in the EU-15 do not differ much for the EU-15 average damage factors for those pollutants. Moreover, and related somewhat to the previous justification, the fact that the standard deviations for the mean damage factors of the targeted air-pollutants as estimated by the ExternE/NEEDS projects have a range between 3 and 4. This indicates that the values estimated could be either 3-4 times greater than the mean value, or 3-4 times less than that value, although and undoubtedly with lower probability of actually being such. This range of uncertainty is due to both the scientific uncertainties involved and the economic valuation uncertainties, both discussed in Chapter 3. The probability that the range of actual damages caused from the release of the selected site-sensitive air borne pollutants in the manufacturing and installation phases of the microgenerators' lifecycle would be similar or within the range specified by the ExternE/NEEDS projects' values is therefore increased. For these above reasons, the study advocates approach 2 as a sufficiently credible methodology to quantify and monetize the airborne environmental implications of the assessed microgenerators.

Approaches 3 and 4 rely on end-point LCIA methods, and therefore the results are tailored to the actual output formats of these methods. Approach 3 used the Eco-indicator 99 (EI-99), and its category of human health, measured through the disability-adjusted life years (DALYs) indicator, and the category of ecosystem quality, measured through the 'potentially disappeared fraction' (PDF) per meter-squared (m²) per year. The resulting quantified environmental impacts are as accurate as the EI-99's 'potential actual impacts' are, in reality, 'actual impacts'. This cannot be known and the EI-99 uses the average European condition (e.g. average population density) as a homogeneous background. The monetization of the environmental

damages through the EI-99 is simplified however, given that only two end-points needed measuring; DALYs and PDF/m²/year. DALYs have been covered extensively in the literature and/or through projects like the ExternE and the NEEDS projects. The adopted value range for DALYs was therefore adopted and adequately supported by these sources, particularly the NEEDS project. On the other hand, the PDF/m²/year indicator was valued through the use of restoration costs as proxy for value from one particular German study. The NEEDS project adopted the restoration costs of 'starting' biotopes to 'target' biotopes (through the use of PDF/m²/year) in the German study and tailored these restoration values for other countries within Europe, including the UK. This part of approach 3 was less certain given that the use of restoration costs as proxy for value of ecosystem damages or improvements has led most probably to an underestimation of the ecosystem value implications.

Approach 4 used the EPS2000 method to account for environmental damages and benefits. This method led to the largest environmental net benefit values, given that it relies directly on the willingness-to-pay (WTP) concept, however using damage values for pollutants that have not been discounted. For example, a DALY is estimated to be 85,000 Euros (2000) in the EPS 2000, while it is estimated at 40,000 Euros (2000) in the NEEDS project. If the EPS 2000 discounted its values, the DALY would have been approximately 50,000 Euros (2000), adopted from the ExternE project. Therefore a 10,000 Euro difference per DALY is down to the difference between the ExternE and the NEEDS DALY values, the latter of which was used in approach 3, and a further 25,000 Euros (2000) difference is down to the use of discounting. The excluding of discounting has led approach 4 to deliver the highest environmental benefits.

The discrepancy in discounting is a limitation elsewhere in the CBA, particularly in the sensitivity analysis of alternative discount rates used. The environmental damage functions have been calculated using a 3% discount rate, and these environmental damages have been adopted, as given, in this study. This presented no problem for the default CBA, as 3% was also selected as the discount rate to be in line with the environmental damage function values. In the sensitivity analysis however, the use of a 3% discount rate on the environmental damages could not be altered (except for discounting the 3% discounted values in future years). Therefore, although 1.5% and 5% discount rates were used, these values affected only the value of electricity and hot water, and the future yearly discounted values of, again, already discounted environmental impact damage functions, but not the original estimates of these damage values.

The different approaches yielded, as expected, different environmental impact results. These results, shown in Figure 5.7, are reproduced below in Figure 9.1 with the respective uncertainty ranges included.

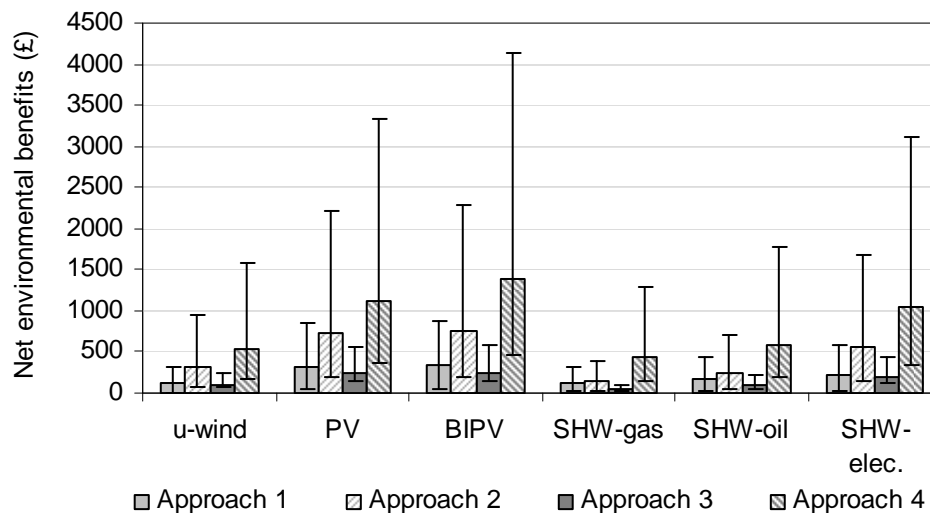


Figure 9-1 Environmental net benefits of the assessed microgenerators

Estimating the environmental damages was not the only demanding task of the CBA applied in this study, however eliciting the true ‘value’ of electricity and hot water also presented a challenge. It was thought that such an elicitation, although subject to considerable uncertainty, would be more impartial or even-handed towards the microgenerators, particularly as the CBA was applied for the valuation of single microgenerators independently, as opposed to a comparison of alternatives which is an objective of cost-effective analysis (CEA). The demand for electricity and hot water were theoretically constructed given the price elasticity of demand for both, coupled with the added assumptions that (1) the elasticity of demand is constant along a pre-defined quantity-price combination, (2) a lower and upper limits to consumption could be (and were) identified, (3) the use of the price discriminating structure of two sampled UK energy suppliers to identify the price elasticity of demand for electricity and the lower and upper energy consumption limits, and (4) the use of the levelised cost of generation with the national composition of the respective hot water boilers as proxy to identify the value for hot water. The value of electricity was estimated to be 16.3 p/kWh and that for hot water estimated at 6.5 p/kWh_{th}.

Returning to Figure 2.9, the quantitative part of the CBA above has turned out negative for most of the microgenerators. Only the microwind system could be given the economic decision to ‘*proceed*’ subject to situating the microwind in a high-wind resource area. However for PV, BIPV, and SHW, the question turns next as to whether the qualitative benefits outlined in Chapter 7 would outweigh the quantitative costs, even under the best case energy outputs of those systems? In other words, are they worth the NPV losses just mentioned earlier, or at least the NPV of the most optimistic case (i.e., minimum capital with maximum energy output assumptions)?

To answer this in a systematic way, Table 9.2 indicates first the ‘best case’ NPVs for the assessed microgenerators (except microwind) taking the mean environmental damage values of approach 2, given the approach’s results are somewhat a compromise between the results obtained from all the approaches. Two attributes,

‘learning externality’ and ‘double dividend effects’, as identified in Chapter 7, are shown next in Table 9.2 and added to the NPV.

	Best case NPV (£)	Learning effect (£)	NPV₁ (£)	Double dividend (£)	NPV₂ (£)
PV	- 3869	672	- 3,197	422	- 2,775
BIPV	- 3,648	672	- 2,976	422	- 2,554
SHW-gas	- 1,703	98	- 1,605	-	- 1,605
SHW-oil	- 1,573	98	- 1,475	-	- 1,475
SHW-elec.	- 1,172	98	- 1,074	-	- 1,074

Figure 9-2 Best case NPV change with internalised learning and double dividends effects

The NPVs are improved by over £1,000 for the PV and BIPV systems, and by approximately £100 for the SHW systems when internalising learning effects and double dividend. However, the NPV are still negative.

The rest of the qualitative arguments for the assessed microgenerators, specifically employment, psychological, local empowerment, network and security of supply could not be monetized. Following the decision-tree of Figure 2.9, when the qualitative part of the CBA cannot be compared or traded off with the quantitative part, and when learning-by-doing externality accounted for above do not impact the conclusion of the results in any significant way, then either a *no-go* decision is called for in this instance, or alternative decision-aiding tools are required.

9.3.2 Financial appraisal;

The financial appraisal (FA) of the microgenerators in Chapter 6 was applied in this study to indicate the individual or household incentives present with respect to installing the selected microgenerators. The costs, including the value added tax (VAT), and the benefits in the form of displaced revenues of electricity, natural gas, or oil were assumed.

A default analysis with constant (in real terms) energy prices revealed that the systems all perform poorly, with the ‘best case’ obtaining a BC ratio of approximately 0.7, pertained to a SHW system displacing electricity. If discounting is neglected, the SHW system displacing electricity just about pays back its initial investment within its 25 lifetime. Possible increases in future energy prices were assumed next in Chapter 6, and consequently the financial performance for all microgenerators improved considerably, yet only with SHW displacing electricity achieving a BC ratio of 1 under the ‘high-high’ fossil fuel scenario.

The systems require(d) therefore substantial government support. Government support was divided in Chapter 6 between current support and proposed support mechanisms. Current support was in the form of grants from the Low Carbon Buildings Program (LCBP), coupled with the two Renewable Obligation Certificates (ROCs) per MWh for the electricity-supplying microgenerators only. The outcome improved the financial attractiveness of all microgenerators, enabling microwind to achieve a BC ratio of almost 1 under a high-wind resource condition with low capital costs. PV and

BIPV achieved BC ratios of over 0.6 under the best solar irradiance condition for the UK. SHW displacing natural gas and oil performed poorly, given that the LCBP grant is applicable only (amounting to £400). It is expected that better support mechanisms for heat would be proposed by the end of 2009 in the UK through the Renewable Heat Initiative.

Proposed financial mechanisms were discussed next for the electricity-supplying microgenerators. The proposed feed-in tariffs (FITs) are being reviewed currently by the UK government, and if they are accepted into statute, they have the potential to dramatically transform the uptake of the assessed microgenerators in the UK. This is so given that microwind, PV, and BIPV all achieve BC ratios of over 1 with their maximum energy output cases. In simple payback times, all systems will now payback well within their lifetimes, under any energy output scenario, with the exception of microwind under a low energy output case.

The total costs of the proposed FITs have been shown to be less than the expected environmental benefits that these systems (microwind and PV/BIPV) achieve, respectively, if environmental quantification approaches 2 and 4 are adopted.

9.3.3 Alternative decision-aiding tools

Two alternative decision-aiding tools, CEA and SMART, were used in Chapter 8 to give a better picture of the assessed microgenerators in the UK context.

The CEA related the microgenerators to other energy generating systems. However, even with the inclusion of avoided network benefits, and the inclusion of the social cost of carbon (i.e., approach 1), the assessed systems have some way to go before they compete with alternatives, with the exception of microwind in a high-wind resourced area. The presentation of results through the levelised cost parameter, where environmental impacts (and other quantifiable implications) can be internalised, is potentially a very informative way to present and compare various energy generating sources.

The SMART analysis performed on the microgenerators in relation to other energy generating sources hoped to include all the attributes that the CBA quantified (especially cost) or could not quantify (for example, psychological impacts). Results of the SMART indicate that the PV/BIPV, microwind, and SHW systems do not perform as badly as they do in the CBA, and other sources, particularly coal-generating electricity or heat, score worse. This gives an indication that the assessed microgenerators should be advocated or at least warrant further analysis. The results however are only indicative, as the analysis could be considered an add-on to the thesis, performed in order to add further perspective on the microgenerators to assist in the decision-making process. This was the case given that the CBA had a substantial qualitative part which renders the NPV criterion incomplete.

In conclusion, it can be said that the assessed microgenerators could play an important, albeit small, role in assisting the UK to meet the targets as set by the Renewable Energy Strategy, specifically in meeting 30% of electricity and 12% of heat from renewable sources, and meeting the target of lowering GHG emissions by 80% in 2050 from a 1990 baseline, with significant progress by 2020. To this end, the

proposed support mechanisms indicated to in the financial appraisal aim to facilitate the assessed microgenerators in order that they compete with alternative conventional sources, and deliver on the energy, environmental, social, and security of supply benefits they have been recognized in achieving.

9.4 Future work

This study is quite broad in its reach, and has tried to link several disciplines together. In doing so, several suggestions for future work are recommended, and they are as follows;

- The analysis of a more representative microwind system in the UK context. As the microwind system analysed in this thesis was relatively very small and too expensive compared to the more purchased systems in the UK, and analysed in this thesis only because of the excellent cooperation between that system's manufacturer and SERT (including the author), analysis of more representative microwind systems are called for.
- Analysis of behavioural aspects of UK householders that may influence the actual output of energy from the assessed microgenerators, thereby their respective energy and environmental impact savings.
- The use of the *Ecosense web 1.3*, an “integrated atmospheric dispersion and exposure assessment model which implements the Impact Pathway Approach developed within ExternE”, to better account for the emissions of important airborne pollutants, and investigating the compatibility of life-cycle assessment output and results with the Ecosense model.
- A *hedonic pricing method* (HPM) to elicit the impact of house properties from the installation of microgenerators. This is vital given that the suggested property value implications of installing these systems are quite high or significant.
- The application of *real options analysis* on the assessed microgenerators, to better account for the uncertainties, particularly the value of the microgenerators' current benefits given the possibility that the future may witness severe resource or environmental limitations on the use of fossil fuels.
- *Strategic analysis* with respect to the benefits of supporting PV and BIPV systems in the UK, given the poor solar irradiance of the Island and as specifically as opposed to waiting until cost reductions in solar panel technologies are achieved through installations elsewhere around the world.
- A comprehensive *multi-criteria evaluation* which can better consolidate the various methodologies or tools used within the ‘integrated appraisal’ and give an indication as to which alternative is preferred, on aggregate.

9.5 Final thoughts

The “*CBA of microgenerators; an integrated appraisal perspective*”, was a broad-reaching study that involved the bringing together of several disciplines in order to analyse the economic and financial performances of the selected energy generating technologies. Given the use (or the need for the use) of a wide-range of tools, the author acknowledges that the depth of this study could be said to be more horizontal than vertical. This is the case precisely for the CBA as a method, given its' requirement to be comprehensive in accounting for all the possible society-wide costs

and benefits of these systems, be they economic, environmental or social in character. As Figure 3.1 of Chapter 3 has illustrated, given that the CBA comes at the end of the ‘integrated appraisal’ assessment, specifically following energy analysis and LCA, it had to be sufficiently informed of these two prior tools and the various options within these tools (for example, different LCIA methods), in order to select the most credible way forward to integrate these tools within CBA and reach a decision with regards to advocating or advising against the selected microgenerators.

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Appendix 1

A brief history of sustainable development

Concern about sustainability emerged in the 18th and 19th century from the publications of Malthus's 'Essay on the Principle of Population' (Malthus, 1798) and 'The Coal Question' by William S. Jevons (Jevons, 1965). Malthus addressed the potential food scarcity and hunger consequences of rising population growth while Jevons focused on the quantitative limits of coal which would not be able to maintain the rising commerce needs of the UK in the later half of the 19th century.

However, it wasn't until the 1960s and 1970s that public opinion began questioning the then conventional, growth-oriented model of economic development due to the rise in environmental degradation and human health consequences associated with unchecked industry (Baker, 2006).

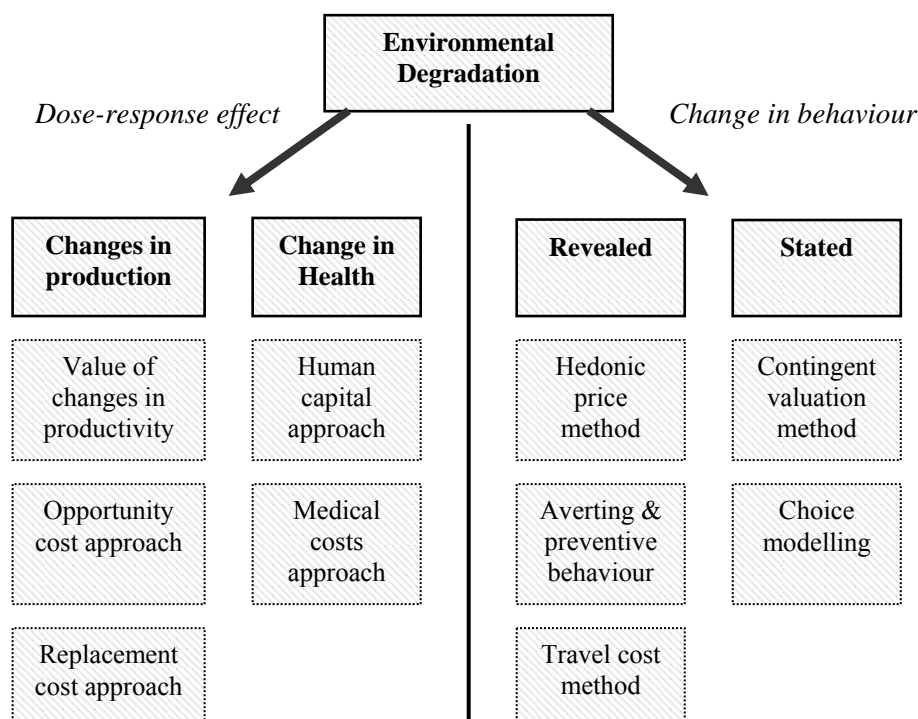
Three further publications paved the way and set up the foundation for the critique and reassessment of the conventional economic growth model. Rachel Carson's 'Silent Spring' (Carson, 1962) significantly raised society's concern in the 1960s about the indiscriminate use of pesticides and insecticides, while Kenneth Boulding's article 'The Economics of the Coming Spaceship Earth' (Boulding, 1966) placed attention to the risks of steadily increasing production levels in terms of depleting finite resources and emitting environmental pollutants, and thirdly 'The Limits to Growth' (Meadows *et al.* 1972) managed to fuel much debate throughout the 1970s although it erroneously assumed a static underlying relationship between the physical, social and economic systems within which exponential industrial capital and population growth levels continue unabated (Cole, 2007).

The term 'sustainable development' however appears to have been first advanced by to the public arena in the early 1980s by the World Conservation Strategy (IUCN, 1980) delivered by the International Union for the Conservation of Nature and Natural Resources (Cole, 2007). Yet the focus of 'sustainable development' bought forth by the IUCN was only positioned on the conservation of living resources, i.e., ecology, and therefore excluded the other two categories, the social and the economic, of what sustainable development encompasses in present day discourse. The discourse which links the social, economic, and environmental dimensions of development were explicitly expressed in the Brundtland Report mentioned above (Baker, 2006).

Appendix 2. Environmental Economics Techniques

Various environmental economics techniques used to monetize costs and benefits in CBA, particularly those that are not reflected in market prices, are outlined in Figure A2.1 and briefly described below. Many of these tools were applied by the ExternE and the NEEDS project to monetize environmental impacts of energy sources.

Figure A2.1. Valuation method techniques for non-market parameters
(World Bank, 2005)



Changes in Production

Dose-response methods require the existence of data linking human, plant or animal physiological response to pollution stress. As an example, if a given level of low-level ozone is associated with crop yield losses, then it is usually the case that the output lost can be valued at market or shadow prices (World Bank, 2005).

Along the dose-response lines the value of changes in productivity, the opportunity cost approach and the replacement cost approach are used to quantify environmental impacts. Productivity loss occurs when there is a change in an environmental input which can lead to a change in the quantity produced resulting in an economic loss that can be measured. Opportunity cost approach is used when the benefits of the activity causing environmental degradation are estimated in order to give a benchmark for what the environmental benefits have to be for the development not to be worthwhile (e.g. drainage of a wetland to allow for intensive agriculture). Replacement costs method regards the cost of replacing or restoring a damaged asset and uses this cost as a measure of the benefit of restoration (e.g. cost of restoring monuments affected by acid rain – usually added to other costs of acid rain affects) (World Bank, 2005).

Changes in Health

The two main categories listed in Figure A2.1 to quantify environmental impacts on health are the human capital approach (also known as the forgone-earnings approach) and the medical cost approach (also known as the cost-of illness approach). The human capital approach attempts to quantify mortality via the net discounted present value of an individual's lifetime earning. In other words it measures the loss of productivity (net present value of productivity) resulting from a person's death or injury. This approach has the advantage of being easily measured, however the main and serious disadvantages are that it may provide biased estimates against women and minorities who tend to have a lower wage rates, it assigns no value to lives of the very old and retired, assigns no value to leisure time, and it does not take into consideration that one's WTP may be considerably different from one's income. The Medical cost approach on the other hand simply estimates the cost of medical treatment for a physically ill patient which resulted from an environmental impact (e.g. air pollution).

Willingness to pay (WTP) studies for a reduction in the risk of death or risk of experiencing illness is used more often however to calculate the value of a statistical life (VOSL) and usually results in higher values than the human capital approach or the medical cost approach as it attempts to measure intangible things such as pain. The value of a statistical life is the amount that people are willing to pay to avoid a risk (or willing to accept to be exposed to a risk) multiplied by the probability of death from that risk. The WTP approach (see also stated valuation methods below) consists of directly asking people through surveys (contingent valuation studies) or assessing from market behaviour their willingness to pay (or willingness to accept) for reduced risks of increased mortality (or increased risk of increased mortality). Summing the total willingness to pay of all concerned members of society will reveal the total value of the benefit or cost in question.

Change in Behaviour **Revealed Preference Methods**

Revealed preference methods involve the estimation of value from observations of behaviour in the markets of related goods. There are basically two main approaches; the travel cost method (TCM) and the hedonic pricing method (HPM).

Hedonic Pricing Method (HPM)

HPM 'attempts to evaluate environmental services, the presence of which directly effects market prices' (Turner *et al.*, 1994). It is based on the theory of consumer behaviour that suggests a good is valued by people due to its characteristics rather than the good itself (Kahn, 1997). The most common application of HPM is the housing market, due to the fact that house prices are affected by a number of factors including the physical qualities (e.g. number of rooms, size of garden...), neighbourhood qualities (e.g. crime rate, proximity to workplace or central district...), and environmental qualities (e.g. existence of nearby park or river, air quality, noise pollution, proximity to quarry or landfill site...) (Turner *et al.*, 1994).

A hedonic price function is determined which relates the price of the property or house to its attributes, including those that have an impact on individual welfare. Mathematically this function can take the following form (World Bank, 2005):

Price of Property = f (Physical attributes, Neighbourhood quality, Environmental quality)

Since different locations have different environmental attributes, such variations will result in different property values. Using statistical techniques, the hedonic approach attempts to identify how much of a property differential is due to a particular environmental difference between properties and infer how much people are WTP for an improvement in the environmental quality that they face (Pearce *et al.*, 1994).

Averting and preventive behaviour

Averting and preventive behaviour is noticed when households, for example, may purchase insulation to defend their homes from noise pollution (as a substitute for a reduction in noise at source) or buying bottled water in place of drinking from polluted tap water. These costs that households make can be added up and estimated.

Travel Cost Method (TCM)

TCM mainly values environmental resources associated with recreational activity. The basic premise to the model is that 'travel cost to a site can be regarded as the price of access to the site' (Kahn, 1997). An on-site questionnaire is used at the recreation site's gate to record how often visitors come to the site, their travel costs to the site, their income... A relationship is then examined through a demand curve showing the overall trend between travel costs and visit rates for all the visitors interviewed. Using this information, an estimate for the average visitor's total recreational value for the site can be approximated and multiplied by the total number of visitors per annum to attain the total annual recreational value of the site (Turner *et al.*, 1994).

Stated valuation method

Contingent valuation method and Choice Modelling

Stated preference techniques directly solicit value measures by asking people hypothetical questions. There are two main types of stated preference techniques, mainly contingent valuation method (CVM) and choice modelling (CM) method.

CM approaches rely on the notion that a good may be described by its attributes. For an example, a forest can be illustrated by its flora and fauna diversity, age structure and recreational facilities (Bateman *et al.*, 2002). In a policy context, CM can tell us four things about non-market goods; namely (1) 'which attributes are significant determinants of the values people place on non-market goods, (2) the implied ranking of these attributes amongst the relevant population(s), (3) the value of changing more than one of the attributes at once, and (4) the total economic value of a resource or good (Bateman *et al.*, 2002).

CVM involves asking a 'randomly chosen sample of people what they are willing-to-pay for a clearly defined change in the provision of a good or service (or to prevent a change) or to illicit what people are willing-to-accept to forgo or tolerate a change' (World Bank, 2005).

Appendix 3

Modelling the social cost of carbon: a simplified illustration – Based on Pearce (2003)

Carbon (or GHG) emissions lead to increased atmospheric concentration, increased atmospheric concentration leads to temperature rise, and temperature rise leads to environmental, economic and social damages, including damages caused by the induced sea-level rise.

Firstly, atmospheric concentrations (C) of carbon and emissions (E) and are linked via Equation A3-1 (Pearce, 2003).

$$C_t = (1 - \frac{1}{L}) \cdot C_{t-1} + \beta \cdot E_t \quad \text{A3-1}$$

where L is the residence time of carbon in the atmosphere and β is a factor that convert emissions (tonnes) into concentrations (parts per million). The first expression on the right-hand side captures the decay process, i.e. the rate at which carbon is removed from the atmosphere, e.g. by oceans (Pearce, 2003).

Secondly, the links between temperature change and changes in carbon concentrations in the atmosphere could be captured, in an oversimplified way, by Equations A3-2 and A3-3 (Pearce, 2003).

$$T_t^U = T_{t-1}^U + \frac{1}{R^U} \left[F_t - \lambda T_{t-1}^U - \frac{R^L}{\theta} (T_{t-1}^U - T_{t-1}^L) \right] \quad \text{A3-2}$$

$$T_t^L = T_{t-1}^L + \frac{1}{R^L} \left[\frac{R^L}{\theta} (T_{t-1}^U - T_{t-1}^L) \right] \quad \text{A3-3}$$

T is temperature, U refers the upper ocean layer and L to the lower ocean layer, r refers to the thermal capacity of ocean layers, F is radiative forcing, θ is the transfer rate between upper and lower ocean layers, and λ is a parameter showing how much temperature changes for a given increase in radiative forcing. I.e. equation A3.3 tries to capture ‘the process whereby radiative forcing heats up the atmosphere, which then heats up the upper ocean, which then heats up the lower ocean’ (Pearce, 2003).

Thirdly, damages and temperature are linked in equation A3-4 (Pearce, 2003).

$$D_t = k_t \left(\frac{T_t^U}{\wedge} \right)^{\gamma} \cdot (1 + \phi)^{t^* - t^{\wedge}} \quad \text{A3-4}$$

The parameter \wedge is the amount of warming (in °C) pertained with a doubling (from pre-industrial levels) of carbon-dioxide (CO₂) concentrations, t^* is the year in which that doubling is expected to occur (usually taken to be 2050). If temperature rises by 1

per cent, damage, D , rises by per cent, i.e. γ links temperature and damage. The symbol ϕ is a parameter that makes impacts greater if they occur before t^* and lower if they occur after t^* , attempting thus to account for damage being related to speed of change. The symbol k accounts for population growth and income expansion, and damage will rise in proportion to these via Equation A3-5 (Pearce, 2003).

$$\frac{k_t}{k_{t-1}} = (1 + \omega \cdot y_t + p_t) \quad \mathbf{A3-5}$$

Where y is rate of growth of income per capita, p is the rate of growth of population, and ω is the income elasticity of willingness to pay to avoid damage.

Appendix 4

LCA results and ExternE/NEEDS damage functions for the centralised systems

ExternE/NEEDS damage functions

The quantified damages of important air-borne pollutants (inputted for approach 2) in the CBA from 1kWh of manufacture and delivery of grid electricity, domestic natural gas and oil are given in Table A4.1.

Pollutant	Grid Electricity (kg per kWh)	Natural gas delivery & use (kg per kWh)	Oil delivery & use (kg per kWh)
Ammonia	0.00001798	3.6015E-07	8.0329E-07
SO ₂	0.00151	0.00012401	0.00044501
NO _x	0.0012	0.00013506	0.00029326
PM ₁₀	0.000515	0.00000977	0.00001723
PM _{2.5}	0.000117	0.0000053	0.00001452
Arsenic	1.3068E-07	4.88E-09	7.028E-09
Cadmium	4.142E-08	1.6E-09	4.74E-09
Chromium	7.788E-08	2.223E-08	2.687E-08
Chromium VI	2.58E-09	5.3218E-10	6.2133E-10
Lead	3.8622E-07	1.89E-08	2.762E-08
Nickel	3.6328E-07	1.336E-08	6.125E-08
Formaldehyde	5.728E-07	3.7427E-07	1.4006E-07
Mercury	0.000000019	2.06E-09	4.68E-09
NM VOC	0.00005532	0.00007326	0.00015375
Nitrates, primary	1.62E-09	2.891E-11	3.437E-11
Sulfates, primary	0.0000016	1.0524E-07	2.2568E-07

Table A4.1. Central system's damages according to ExternE/NEEDS projects

LCA results

Central grid electricity

The UK 2008-2009 national electricity grid pollutant mix (1 kWh) according to the EI-99 is presented in Table A4.2 below, while the EPS2000 LCIA results are presented in Table A4.3.

Eco-indicator 99 (EI-99)		
Impact category	Unit	Total
Carcinogens	DALY	5.29E-08
Resp. organics	DALY	1.04E-10
Resp. inorganics	DALY	2.04E-07
Climate change	DALY	1.24E-07
Radiation	DALY	5.67E-09
Ozone layer	DALY	3.01E-11
Ecotoxicity	PAF*m2yr	0.03363
Acidification/ Eutrophication	PDF*m2yr	0.006349
Land use	PDF*m2yr	0.002078
Minerals	MJ surplus	0.00104
Fossil fuels	MJ surplus	0.548864

Table A4.2. UK grid energy pollutant mix (1 kWh) according to the EI-99

EPS2000		
Impact category	Unit	Total
Life expectancy	ELU	0.056332
Severe morbidity	ELU	0.020278
Morbidity	ELU	0.004101
Severe nuisance	ELU	0.000269
Nuisance	ELU	0.001279
Crop growth capacity	ELU	0.000168
Wood growth capacity	ELU	-0.001
Fish and meat production	ELU	-2.7E-05
Soil acidification	ELU	3.45E-05
Prod. cap. irrigation Water	ELU	0
Prod. cap. drinking water	ELU	0
Species extinction	ELU	0.000787

Table A4.3. UK grid energy pollutant damage assessment (per kWh) according to the EPS2000

Natural gas

The UK 2008-2009 domestic natural gas delivery and use pollutant mix (1 kWh) according to the EI-99 and EPS 2000 in Tables A4.4 and A 4.5, respectively below.

Eco-indicator 99 (EI-99)		
Impact category	Unit	Total
Carcinogens	DALY	9.55E-11
Resp. organics	DALY	1.07E-11
Resp. inorganics	DALY	1.86E-09
Climate change	DALY	4.13E-09
Radiation	DALY	9.16E-12
Ozone layer	DALY	2.75E-12
Ecotoxicity	PAF*m2yr	4.49E-04
Acidification/ Eutrophication	PDF*m2yr	6.99E-05
Land use	PDF*m2yr	6.27E-05
Minerals	MJ surplus	1.19E-04
Fossil fuels	MJ surplus	4.44E-02

Table A4.4. UK natural gas delivery and use (per kWh) according to the EI-99

EPS2000		
Impact category	Unit	Total
Life expectancy	ELU	1.59E-03
Severe morbidity	ELU	7.44E-04
Morbidity	ELU	1.32E-04
Severe nuisance	ELU	4.25E-06
Nuisance	ELU	9.31E-06
Crop growth capacity	ELU	5.12E-06
Wood growth capacity	ELU	-3.05E-05
Fish and meat production	ELU	-3.54E-07
Soil acidification	ELU	2.72E-07
Prod. cap. irrigation Water	ELU	0.00E+00
Prod. cap. drinking water	ELU	0.00E+00
Species extinction	ELU	2.82E-05

Table A4.5. UK natural gas delivery and use (per kWh) damage assessment according to the EPS2000

Oil

The UK 2008-2009 domestic oil delivery and use pollutant mix (1 kWh) according to the EI-99 and EPS 2000 are given in Tables A4.6 and A4.7, respectively below.

Eco-indicator 99 (EI-99)		
Impact category	Unit	Total
Carcinogens	DALY	1.74E-10
Resp. organics	DALY	1.84E-11
Resp. inorganics	DALY	5.35E-09
Climate change	DALY	5.46E-09
Radiation	DALY	1.84E-11
Ozone layer	DALY	4.00E-12
Ecotoxicity	PAF*m2yr	9.77E-05
Acidification/ Eutrophication	PDF*m2yr	1.76E-04
Land use	PDF*m2yr	2.10E-04
Minerals	MJ surplus	1.54E-04
Fossil fuels	MJ surplus	5.02E-02

Table A4.6. UK oil delivery and use (per kWh) characterized according to the EI-99

EPS2000		
Impact category	Unit	Total
Life expectancy	ELU	0.00208
Severe morbidity	ELU	0.000899
Morbidity	ELU	0.000176
Severe nuisance	ELU	6.57E-06
Nuisance	ELU	3.05E-05
Crop growth capacity	ELU	6.52E-06
Wood growth capacity	ELU	-4.4E-05
Fish and meat production	ELU	-8E-07
Soil acidification	ELU	8.41E-07
Prod. cap. irrigation Water	ELU	0
Prod. cap. drinking water	ELU	0
Species extinction	ELU	3.73E-05

Table A4.7. UK oil delivery and use (per kWh) damage assessment according to the EPS2000

Appendix 5

Costs of generating sources; references used for the CEA

Particular Technologies

Nuclear

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PV

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Appendix 6

SMART Questionnaire for selected attributes

Dear SERT

I am performing a *simple multi-attribute rating technique* (SMART) on some energy generating sources (specifically PV, microwind, large wind, hydro, nuclear, coal and natural gas plants). Can I kindly trouble you to compare the relative importance of the below specified attributes concerning the generating sources, given that I have by default stated that cost is the most important attribute (and therefore ranked it 100%)?

Attributes;

- **Cost** (estimated through the levelised cost indicator)
- **Capacity Factor** (an indication of intermittency and reliability)
- **Security of Supply** (measured through the independence of an energy source from foreign energy resources)
- **Flexibility of dispatch** (how flexible an energy generating source is to respond to energy demand fluctuations and needs)
- **Environmental impacts**, including greenhouse gases.
- **Employment**; or the ability to create employment
- **Energy** (energy gain ratio)
- **Learning** (i.e., immature technologies have a lot cost cutting to be realised, which is a benefit in itself)
- **House value** (some technologies if installed on or near a house may increase, such as PV, or decrease, such as a nuclear power plant, house value)
- **Double dividend** (this is only targeted at microgenerators, saying that they may induce a reduction in overall energy demand if accompanied by a smart meter)
- **Psychological effects**; again some people may reap personal gratification from installing a renewable energy system for example, just as they may suffer from knowing they live in the vicinity of a nuclear or coal power plant. Also, for example, some local people may feel empowered about the fact that their energy sources are locally produced, as opposed of the feeling that their incomes are being transferred to faraway places.

For example (again cost is 100% by default), you may say that the ‘capacity factor’ attribute should be 70% as important as cost in deciding whether to go for a certain technology, and that environmental impacts are 50% as important, and so forth, so in the end you may have something like (*a totally random example*);

Cost	100%
Environmental impacts	70%
Energy	60%
Flexibility of dispatch	60%
Double dividend	55%
Learning	50%
House value	50%
Capacity factor	40%
Security of supply	35%
Psychological effect	30%

Employment

20%

So you are saying that the 'employment' attribute, which could mean the ability of the technology to promote employment opportunities, should be given 20% the importance of cost in deciding for an alternative generating source, for example.

I know there are so many other indicators that can be used to decide if a generating source is worthwhile, but I selected the above given their relation to microgeneration. If you feel I missed out on a very critical and important indicator, please do also let me know. Thank you very much for helping me in this, and if you need any further clarification as to the attributes used above, please do let me know.

Sincerely,

Hassan

Appendix 7

Email correspondences

Email 1. Garrod, N. (Nigel.Garrod@veolia.co.uk), 16th September 2008. *Price for hot water delivery in the UK.* Email to H. Harajli. (hh237@bath.ac.uk)

Hassan

From: Garrod, Nigel [Nigel.Garrod@veolia.co.uk]
Sent: 16 September 2008 15:25
To: hh237@bath.ac.uk
Subject: Re: Veolia Sheffield

Hassan,

Thank you for your email.

This is not an easy question due to commercial confidentiality issues and due to the fact that we have various different tariff rates. We actually sell very little energy direct to householders as in most cases we sell in bulk to the building and others invoice the householder/tenant. In effect we sell wholesale and someone else retails the energy.

If you worked on 3.0 to 3.5p/kWh you will be in the right ballpark for 2008.

Regards,

Nigel Garrod
Director of Operations
Energy Recovery
Veolia Environmental Services (United Kingdom) Lumley Street Service Centre Lumley
Street Sheffield
S4 7ZJ

Telephone 0114 228 3682
Mobile 07786 171936
-----Original Message-----
From: SheffieldEnquiries
Sent: 16 September 2008 12:26
To: Garrod, Nigel
Subject: FW: Contact Form from
www.VeoliaEnvironmentalServices.co.uk/sheffield

-----Original Message-----
From: webserver@veoliaadmin.co.uk [mailto:webserver@veoliaadmin.co.uk]
Sent: 15 September 2008 12:16
To: SheffieldEnquiries
Subject: Contact Form from
www.VeoliaEnvironmentalServices.co.uk/sheffield

The following Contact Form has been submitted :

Name : Hassan Harajli

Address 1 : University of Bath
Address 2 :
Address 3 :
Town/City: Bath
County : Bath and NE Somerset
Postcode : BA27AY

Contact Number : 01225385164

Email : hh237@bath.ac.uk

Regarding : Education, Energy Recovery

Query or Comment :
My name is Hassan Harajli and I am a PHD student at the University of Bath
where part of my research is focused on the integrated assessment of

microgenerators, among which are solar hot water and micro-chp systems
as
part of the SERT team (my profile; <http://people.bath.ac.uk/hh237/>).

I am trying to obtain the 'value' of hot water to householders in the
UK.
If hot water is being delivered directly (for heating or bathing
purposes)
and charged accordingly it is important for me to get a picture of the
price householders pay for that hot water currently.

Therefore, if it isn't too much trouble and if it does not violate any
confidentiality issue, I would very much appreciate any assistance in
this
regards, specifically how much (on average) is the householder charged
per
kWh of delivered heat?

Respond via : Email, Phone

End of Submission.

As an environmentally conscious company, Veolia Environmental Services is keen to help
save trees by reducing paper usage. Please only print out this email if absolutely
necessary. In 2007 the UK used about 12.1 million tonnes of paper of which 71% was
recovered.

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it. Our registered office is at Veolia House, 154A Pentonville Road, London, N1 9PE.
Registered in England 2215767.

Email 2. Reed, E. (emma.reed@decc.gsi.gov.uk), 24th July 2009. *Quarterly energy prices and electricity consumption*. Email to H. Harajli (hh237@bath.ac.uk).

Hassan

From: Reed Emma (DECC CSSS) [emma.reed@decc.gsi.gov.uk]
Sent: 24 July 2009 15:18
To: hh237@bath.ac.uk
Subject: Electricity consumption

Hassan,

Following on from our phone conversation earlier, you asked about the consumption level of 3300kwh for electricity.

For the Quarterly Energy Prices publication we produce average bills over time. To allow a comparison over time, the same electricity consumption is assumed for each year - 3300kwh per household per annum.

Actual electricity consumption is a little higher. The Digest of UK Energy Statistics has data on total domestic consumption (Table 5.1; 115,000 GWh) from which an average consumption per household can be estimated. Approx average of 4500kwh across all households. However, under 20% of households are on economy 7 whilst the remaining 80% on standard electricity which is closer to around 4000kwh per annum on average. Theoretically, you could broadly approximate a bill at these consumption levels by dividing by 3300 and multiplying by the desired consumption level.

<http://www.berr.gov.uk/energy/statistics/publications/dukes/page45537.html>

The key issue here is being able to compare bills over time when consumption is held constant. We also include in QEP the Retail Price Index for electricity prices that may also be of interest to you (Table 2.1.1 & 2)

I hope that helps.

Kind Regards,

Emma
Emma Reed, Fuel Poverty and Domestic Energy Prices
Department of Energy and Climate Change
Tel: 0300 068 5039

Appendix 8 Publications

The following papers are reproduced in this appendix, the first four of which have been either published, and the last of which are in the review process of being published.

Accepted/published journals and/or conference papers;

1. Allen, S. R., Hammond, G. P., Harajli, H. A., Jones, C. I., McManus, M. C., & Winnett, A. B. 2008a. "Integrated appraisal of micro-generators: methods and applications", *Proc.Instn Civil Engrs: Energy*, vol. 161, no. 2, pp. 73-86. This paper is a revised and extended version of work originally presented at the '1st International Conference on Micro-Cogeneration Technologies and Applications' (Micro-Cogen 2008), Ottawa, Canada, 29 April - 1 May 2008, Paper MG2008-SG-005, 8pp.
2. Allen, S.R., Hammond, G. P., Harajli, H.A., McManus, M.C., & Winnett, A.B. 2010. "Integrated appraisal of solar hot water systems", *Energy*, vol. 35, pp. 1351-1362.
3. El-Fadel, R.H., Hammond, G.P., Harajli, H.A.* , Jones, C.I, Kabakian, V.K., Winnett, A.B. 2010. "The Lebanese electricity sector in the context of sustainable development", *Energy Policy*, vol. 38, pp. 751-761.
4. Hammond, G.P., Harajli, H.A., Jones, C.I., Winnett, A.B., 2009. Integrated appraisal of building integrated photovoltaic (BIPV) systems. Proceedings of the First International Conference on Sustainable Power Generation and Supply (Supergen), Nanjing, China, April 6-7.

Journals in the review process;

5. Hammond, G.P., Harajli, H.A., Jones, C.I., & Winnett, A.B 2009b. "Whole systems appraisal of a Building Integrated Photovoltaic (BIPV) system; energy, environmental and economic evaluations", *Submitted to Energy Policy, awaiting feedback.*

* Corresponding author;

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Tel.: +44 1225 385164, fax: +44 1225 386928, Email address: hh237@bath.ac.uk